NASA CR-188266

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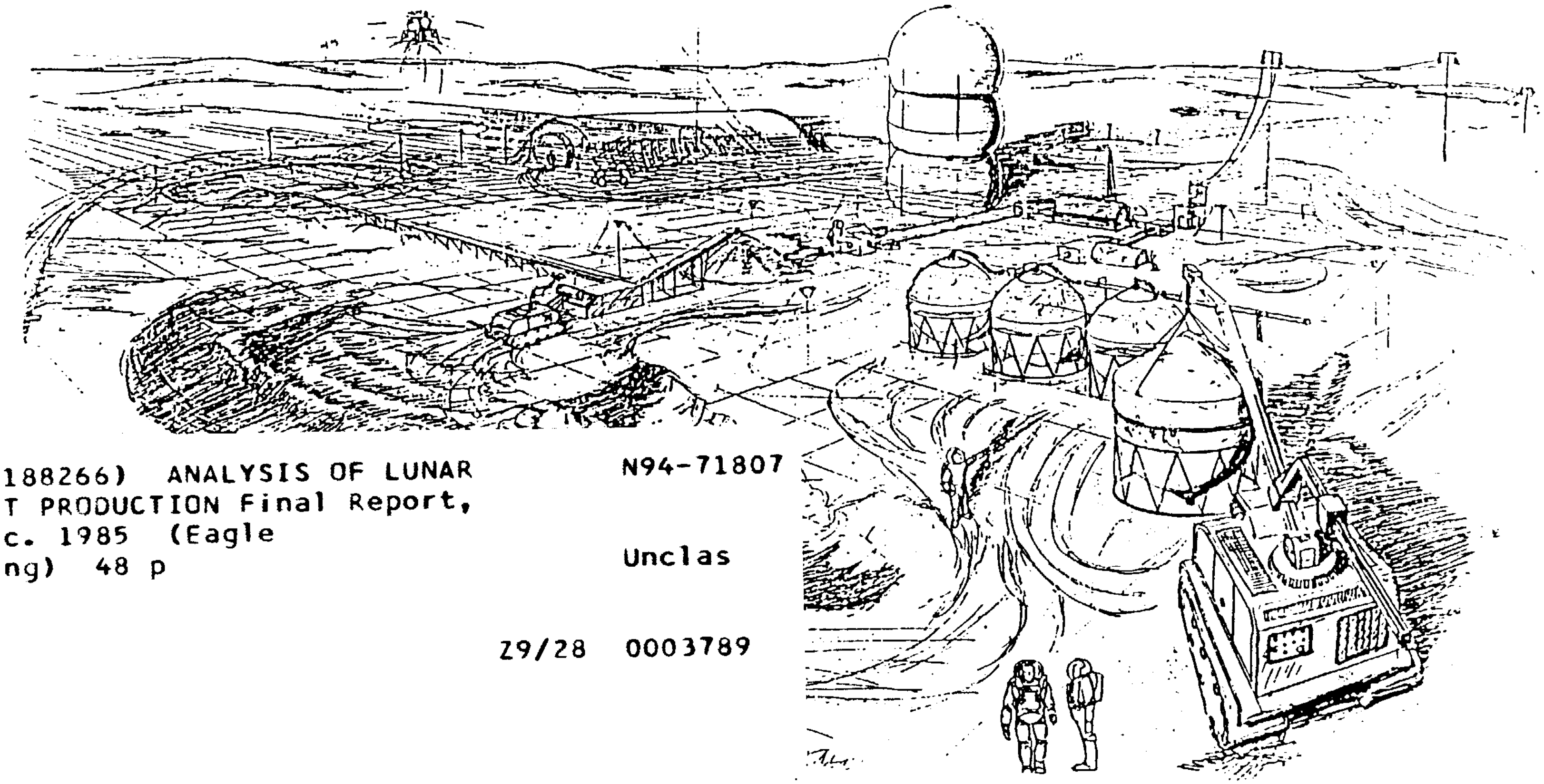
Analysis of Lunar Propellant Production



(NASA-CR-188266) ANALYSIS OF LUNAR PROPELLANT PRODUCTION Final Report, Aug. - Dec. 1985 (Eagle Engineering) 48 p

N94-71807

Unclas

Z9/28 0003789

EEI- 85 - 103B FINAL

December 9, 1985

EAGLE ENGINEERING, INC.

Foreword

This work was conducted between August and December of 1985 by Eagle Engineering for the Advanced Programs Office of the Johnson Space Center. The original purpose of the work was to develop a methodology for the study of lunar propellant production. Many of the numbers contained in this work are therefore place holders. Once the methodology was developed, however, it was irresistible not to apply it to cases of interest. The most valuable result of this work is, nevertheless, the methodology and not the results of its perhaps premature application.

Barney Roberts was the NASA technical monitor for this task. Bill Stump was the Eagle project manager. Other Eagle team members included Gus Babb, Eric Christiansen, Don Sullivan, and Pat Rawlings. Andy Cutler (Calspace), Mike Simon (General Dynamics), Chris Knudsen (Carbotek), and Wendell Mendell (NASA JSC) all provided valuable inputs.

A menu-driven Lotus program for IBM compatible machines that does the calculations and produces the fourteen tables contained in this document is available from Eagle Engineering. Contact Bill Stump or Eric Christiansen at Eagle in Houston.

Analysis of Lunar Propellant Production

Summary

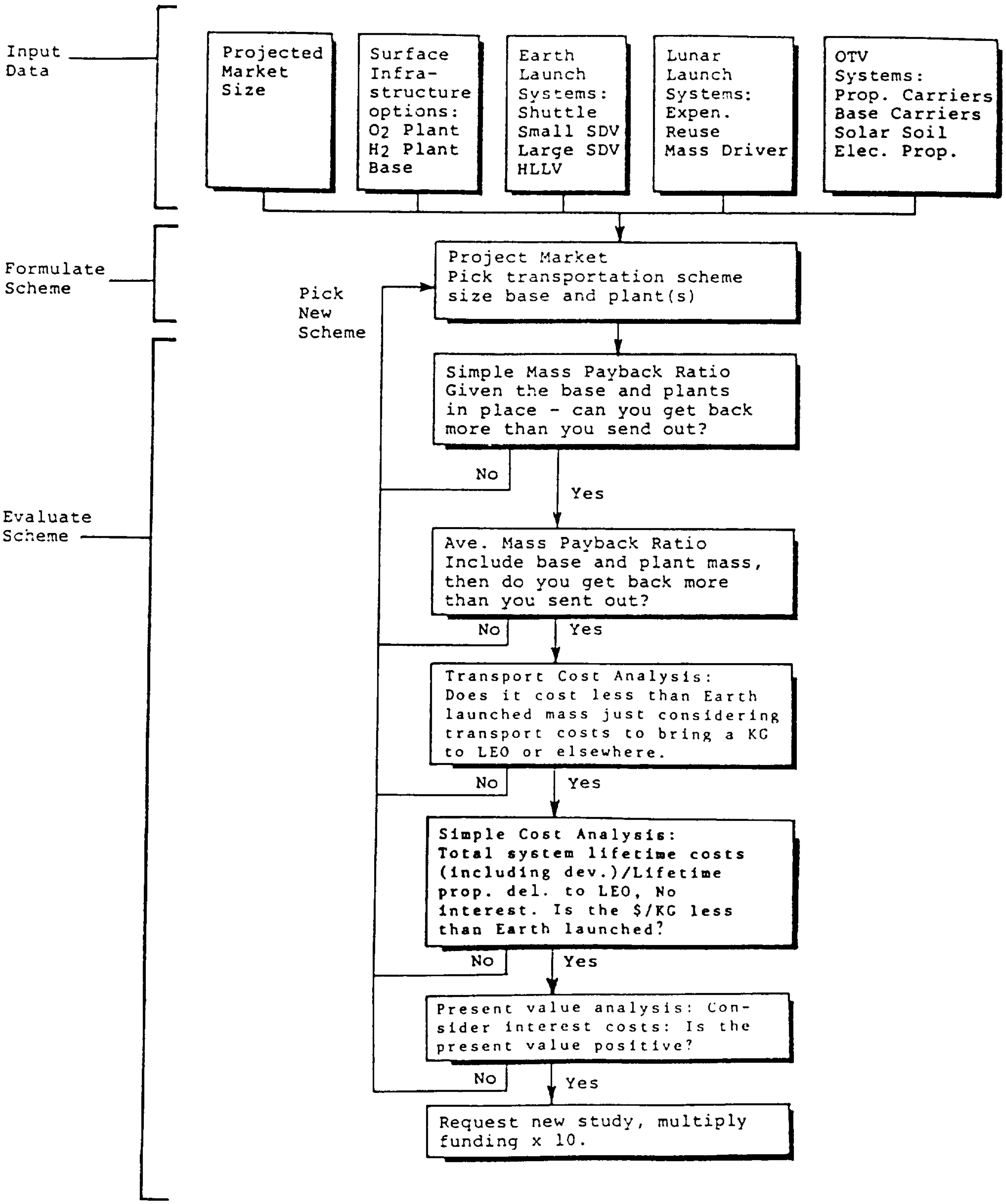
A methodology for the analysis of lunar propellant production schemes is developed. This methodology was first applied to the case of approximately 1,400 metric tons (MT) per year of lunar produced oxygen delivered to low Earth orbit (LEO) by a variety of propulsion schemes, some of which include the use of lunar hydrogen. Given many assumptions concerning cost, it appears difficult to deliver oxygen to LEO for less than the projected delivery cost of a large Shuttle derived vehicle (SDV). The projected cost difference between the two methods of delivery is not large however, a factor of two or less in most cases. An increase in the market size in LEO to 4,316 metric tons/year further narrows the cost difference. Minimum development and transportation of infrastructure costs of 30 to 60 billion dollars are estimated. The development cost estimate does not include the SDV or base lander orbital transfer vehicle (OTV), and includes only 50 percent of the minimum surface base development costs. If the government absorbs this 30 to 60 billion up front capital cost, and does not require payback, oxygen delivery to LEO may be profitable, particularly for the large market case.

Methodology

Figure 1 shows the overall methodology of the program. In simple terms, data is collected, a scenario or scheme formulated, and the scenario evaluated. There is a temptation to go directly from a scheme formulation to cost per kg of the product at its destination.

FIGURE 1

Economic Analysis of Lunar Propellant Production



Cost is difficult to estimate and the validity of such a cost per kg estimate is easily questioned. The methodology shown here proposes that each new scheme be exposed at each of a series of simple, but increasingly complex evaluation calculations. Each calculation is a more complex filter.

The first filter proposed is the simple mass payback ratio. Assume all the plants and transportation system in place, will the operating, steady state transportation system return significantly more mass than must be sent out?

If so then add in all the infrastructure (which may be more difficult to estimate) that must be put in place for this scheme. The average mass payback ratio is then computed as the total product returned over the total material shipped out.

If the average mass payback ratio is sufficiently large, then a transport cost analysis is performed. Estimate only the operations cost of transport of the materials back to Earth or elsewhere, do not include development of vehicles or infrastructure or placement of infrastructure.

If the cost/kg for transport operations is not too large compared to costs for competitive transport systems, then try to estimate the total system lifetime costs, including development, vehicle and infrastructure, operations, etc. Divide this cost by the total lifetime market.

If this cost/kg is not too large compared to competitive system costs, then do a present value analysis of the scheme, which includes the interest cost of the initial capital investment (development and infrastructure placement). If the net present value is positive, the proposed scenario has some economic merit, and would, by virtue of passing

through each successive filter, be suitable for further analysis and development.

This kind of analysis exposes the scenario to the reader at increasing levels of complexity such that, even if the reader has no confidence in the author's ability to estimate program costs (often justified), the less debatable evaluations are visible and the reader can draw his own conclusions independent of all the cost numbers.

A Test Case - Lunar Propellant Production for Delivery to LEO

The above described methodology was applied to the case of lunar produced oxygen delivered to LEO. Each of the following fourteen tables is a step in this methodology. The lunar oxygen to LEO case was chosen because, if it can be made to work, it could become a sufficient reason to establish a large manned presence on the Moon. Markets other than LEO will probably exist for lunar produced oxygen. It would be much easier to economically justify lunar oxygen consumed on the lunar surface or in lunar orbit, but the consumers will then be there for other reasons and perhaps at a much later date. A market for oxygen in GEO may exist also, though in an era of large aerobraked orbital transfer vehicles (OTVs) it may not be large.

The question for this test case is therefore: should the U.S. sponsor a return to the Moon to get oxygen for LEO operations. A variety of transportation schemes are to be addressed. All costs available (limited by the scope of the study) are to be included. The analysis done here is not complete enough to answer this question with a strong yes, but it is complete enough to say no for some scenarios. To say yes strongly will require the accurate determination of many (mostly cost) numbers.

The following tables document the program. The values in the tables come in three catagories, wild guess, guess, and no comment. The wild guess numbers are pulled out of the air for lack of better knowledge on the part of the authors. The guess numbers have a basis in fact but are still suspect. The numbers with no comment have some validity or are calculated values (although they may sometimes be based on wild guesses). A Lotus spreadsheet was developed to generate these tables. The program is menu driven to allow the user to readily alter the independent variables and determine their impact on the analysis of lunar propellant production.

Tables 1 through 6 are the "input data" step in the methodology. Table 1 shows the projected market in LEO. The largest market is for the Strategic Defense Initiative (SDI) and manned Mars missions. If either one or both of these come to pass, there will be a significant market for oxygen in LEO. A key number is the fraction of the SDI total LEO mass assumed to be propellant. The annual market numbers in Table 1 were taken from a peak year in the Ref. 1 model and represent a projected annual maximum more than an average number. A maximum was used, because, as noted earlier, it is possible to prove some schemes will not work with this model by using optimistic extreme numbers, but it is not really possible to prove they will work without much more accurate cost numbers. Other numbers in this analysis were also chosen with this in mind. The positive proofs are left for later studies.

The projected lunar surface (LS) and low lunar orbit (LLO) propellant markets were not considered in the analysis of lunar propellant production for the projected LEO market

TABLE 1 - PROJECTED MARKET

PROJECTED ANNUAL
LEO MARKET (taken from Reference 1)

Program (Year 2005)	Total Mass to LEO, MT	Fraction of Mass assumed to be prop.	Total Propellant in LEO, MT	Assumed Mixture Ratio	Oxygen Propellant in LEO, MT	Hydrogen Propellant in LEO, MT
LEO Servicing	118	0.3	35	7	31	4
LEO Communication	59	0.6	35	7	31	4
LEO DOD	118	0.3	35	7	31	4
LEO Space Station	136	0.3	41	7	36	5
GEO Manned Sortie	45	0.6	27	7	24	3
Planetary	30	0.7	21	7	18	3
Lunar Base (Ref.2)	630	0.7	441	7	386	55
SDI	11,272	0.3	3,382	7	2,959	423
Mars Missions	1,307	0.7	915	7	801	114
Total	13,715		4,933		4,316	617
Total less SDI	2,443		1,551		1,357	194
Total less SDI and Mars Missions	1,136		636		557	80

ANNUAL MARKET LUNAR SURFACE AND LOW LUNAR ORBIT	Total Mass to Lunar Orbit, MT	Fraction of Mass assumed to be prop.	Total Propellant MT	Assumed Mixture Ratio	Oxygen Propellant MT	Hydrogen Propellant MT
Lunar Orbit Market	140	0.4	56	7	49	7
Lunar Surface Market	140	1.71	239	7	209	30

but are included for comparison purposes in Table 1. Though these markets are much more likely to be economically attractive, they are not in themselves reasons to return to the Moon.

Table 2 attempts to approximately size the oxygen and hydrogen plants for two cases: 1. when only lunar oxygen is available for recovery and 2. when both lunar oxygen and hydrogen are available. In the case where only oxygen is available, the oxygen plant becomes much larger to support increased transport activity moving hydrogen. The plants were sized for different LEO propellant markets by using a ratio of plant mass to production based on several studies (References 3 and 4). Most research has focused on sizing the oxygen plant. The oxygen plant was scaled as a function of capacity at less than the 1^{st} power (ie. the specific mass ratio decreases as plant capacity increases). Figure 2 illustrates a JSC ilmenite concept sized by Eagle Engineering. Limited data (Ref. 6) was available on hydrogen plants. It is not at all clear that a practical hydrogen extraction process is technically feasible or that hydrogen exists on the Moon in usable quantities. The hydrogen is needed however, because for the conventional propulsion alternatives, lunar supplied oxygen alone can probably not be economically transported to LEO. It was assumed a hydrogen plant would scale roughly with production. The cost numbers for these plants were simply scaled on mass, which is uncertain for the hydrogen plant. All cost numbers in this analysis are in 1985 dollars in this and all following tables.

A minimum base mass (which might be an addition to another base) to support these plants was assumed. The base mass was held constant for all cases, but should be scaled

TABLE 2 - O2 & H2 PLANTS AND MINIMUM BASE

SURFACE INFRASTRUCTURE	Large O2 Plant for Total O2 Market	Medium O2 Plant for Total less SDI	Small O2 Plant for Total less SDI & Mars Mis.	Large H2 Plant	Medium H2 Plant	Small H2 Plant	Minimum Base to Support Plant
				(H2 is used only in OTVs and landers, not sold)			
Plant specific mass, MT/MT per year product (Ref.3 and 4)	0.15	0.20	0.25	1 (wild guess)	1 (wild guess)	1 (wild guess)	
LEO market, MT/year	4,316	1,357	557	0	0	0	
Lunar propellant production ratio (Total prop. produced/O2 delivered to LEO) O2 plant only case - from col. 1 in Table 7	4.52	4.52	4.52				
Lunar propellant production ratio (Total prop. produced/O2 delivered to LEO) O2 & H2 plant case - from col. 2 in Table 7	2.17	2.17	2.17				
MT H2 prod. req./MT O2 del. to LEO	0	0	0	0.28	0.28	0.28	
Total production, O2 only case, MT/year	19,527	6,140	2,518				
Total production, O2 & H2 case, MT/year	9,355	2,942	1,206	1,192	375	154	
Plant Mass, MT (O2 only case)	2,929	1,228	628				87.5 (5 landings)
Plant Mass, MT (O2 & H2 case)	1,403	588	301	1,192	375	154	87.5 (5 landings)
Power Req., O2 only case, MW (3.3 KW/MT per year for O2)	64	20	8				100
Power Req., O2 & H2 case, MW (3.3 KW/MT per year for O2)	31	10	4				
Fraction of base or plant mass that is resupplied each year	0.02 (wild guess)	0.02 (wild guess)	0.02 (wild guess)	0.02 (wild guess)	0.02 (wild guess)	0.02 (wild guess)	0.02 (wild guess)
Resupply mass, O2 only case, MT/year	59	25	13				1.75
Resupply mass, O2 & H2 case, MT/year	28	12	6	23.84	7.50	3.07	1.75
Crew on lunar surface/MT per year prod.	0.002 (guess)	0.002 (guess)	0.002 (guess)	0.005 (guess)	0.005 (guess)	0.005 (guess)	0.005 (guess)
Crew on the lunar surface, O2 only case O2 plt: (10+Crew constant*Prod.)	49	22	15	0	0	0	
Crew on the lunar surface, O2 & H2 case add-on for H2 plt: (Crew const*Prod)	29	16	12	6 (add-on crew for H2 plant)	2	1	
Plant life, years	20 (wild guess)	20 (wild guess)	20 (wild guess)	20 (wild guess)	20 (wild guess)	20 (wild guess)	
Development cost, O2 only case, billion $ (5,000 $/KG of plant mass)	15 (guess)	6 (guess)	3 (guess)				5 (guess)
Development cost, O2 & H2 case, billion $ (5,000 $/KG of plant mass)	7 (guess)	3 (guess)	2 (guess)	5.96 (guess)	1.87 (guess)	0.77 (guess)	
Operations cost, million $/year	100 (wild guess)	100 (wild guess)	100 (wild guess)	100 (wild guess)	100 (wild guess)	100 (wild guess)	100 (guess)

FIGURE 2 - LUNAR OXYGEN PLANT

with the size of the crew needed to run the plant(s). This crew size, as shown on the chart, is uncertain but may be large. The minimum base chosen is therefore conservative.

Table 3 shows a set of possible Earth surface to LEO launch systems. The costs are somewhat uncertain, but nowhere near as uncertain as other cost numbers used. A number of major significance is the cost per kg or mission for the next generation heavy lift or Shuttle derived vehicle. Some will debate that the development and operations cost of this vehicle, which will be used to carry propellants most of the time, is much greater than shown here, perhaps by a factor of four. This would seem to make lunar produced propellants more competitive. On the other hand, the lunar surface infrastructure must be put in place with propellant launched with this vehicle, therefore the capital costs also rise dramatically, increasing the cost of lunar produced propellant. Future work should include a sensitivity study of these scenarios to the operations cost of these heavy lift vehicles. The Lotus program developed here could be used, or a later version of it.

Table 4 is a set of orbital transfer vehicles (OTVs) sized to carry lunar produced oxygen from LLO to LEO. These vehicles were sized to return payloads to LEO in the 100 MT range to accommodate a greater than 1,000 MT/year LEO propellant market. The best payload size for these OTVs is subject to some debate. The 100 MT size range was chosen because cost/kg transported generally goes down as the payload of an individual vehicle goes up and 100 MT resulted in about as large an OTV as the authors felt was practical to handle with projected infrastucture for maintenance, transport, etc.

For conventional propulsion, large aerobrakes will be required to brake the propellant loads into LEO. These vehicles were assumed to be specially designed for the propellant

TABLE 3 - EARTH LAUNCH SYSTEMS

EARTH LAUNCH SYSTEMS (Surface to 500 km LEO)	Shuttle	Small SDV	Large SDV	Heavy Lift Launch Veh.
Max. possible payload, MT	25	68	100	250
Max. O_2 payload, MT (.95 multiplier for tank factor)	23.75	64.6	95	237.5
Max. H_2 payload, MT (.7 multiplier for tank factor)	17.5	47.6	70	175
Launch cost (one mission, operations only), million $	114	177	134	150
General payload transportation to LEO cost, K$/Kg	4.56	2.60	1.34	0.60
O_2 transportation to LEO cost, K$/Kg	4.80	2.74	1.41	0.63
H_2 transportation to LEO cost, K$/Kg	6.51	3.72	1.91	0.86
Development cost, billion $	7.3	2.8	3.5	8
Years required to develop	10	5	5	10

TABLE 4 - PROPELLANT CARRIER OTVS

SPACE BASED, AEROBRAKED OTV PROPELLANT CARRIER	Cryogenic O2/H2 LEO-GEO-LEO	Cryogenic O2/H2 LEO-LLO-LEO	Cryogenic O2/H2 LLO-LEO-LLO	Cryogenic O2/H2 LLO-LEO-LLO	Cryogenic O2/H2 LLO-LEO-LLO	Cryogenic O2/H2 LLO-GEO-LLO	O2 Nuc.Elec. 5,000 sec Isp LLO-LEO-LLO	Solar Sail LLO-HLEO-LLO
Mission	round trip retrn empty	round trip retrn empty	round trip retrn empty	round trip retrns H2	round trip retrn empty	round trip retrn empty	round trip retrn empty 1 yr r-trip	round trip retrn empty or with payld
Load H2 in:, O2 in:	LEO, LEO	LEO, LEO	LLO, LLO	LEO, LLO	LEO,LLO	LLO,LLO	LLO	
Inert mass, MT	7	7.6	26.4	25 (guess)	24	6.8	40 (5 MW/MPD)	400 (JPL veh. scale up, may need to operate frm high LEO)
Aerobrake fraction, %	15	10	10	5	10	0	0	
Boiloff, MT/day	0	0.2	0.2	0	0.2	0.2	0	
Start burn mass, MT	58	158.8	243.6	177.5	220	237.6	340 (guess)	500
Max. possible payload, MT	9 (to GEO)	51.2 (to LLO)	117.2 (to Earth)	52.5 *(to Earth)	96 (to Earth)	130.8 (to GEO)	240 (guess)	100
Max. O2 payload, MT (.95 of max. payload)	8.55	48.64	111.34	49.875	91.2	124.26	228	95
Max. H2 payload, MT (.7 of max. payload)	6.3	35.84	82.04	36.75	67.2	91.56	168	70
Total Propellant Mass, MT	42	100	100	100	100	100	63 (guess)	(lose 10% of sail every 4 years)
Mixture Ratio	7	7	7	7	7	7		
O2 Propellant, MT	36.75	87.5	87.5	87.5 (load LLO)	87.5 (load LLO)	87.5 (load LLO)	60 (load LLO)	
H2 Propellant, MT	5.25	12.5	12.5	12.5 (load LEO)	12.5 (load LEO)	12.5 (load LLO)		
One mission costs, K$ (ops and airframe amortization)	18,500	18,500	18,500	18,500	18,500	18,500	56,000	18,500
General payload transportation cost, $/Kg	2,056	361	158	352	193	141	233	185
O2 transportation cost, $/Kg	2,164	380	166	371	203	149	246	195
H2 transportation cost, $/Kg	2,937	516	225	503	275	202	333	264
No. of missions veh. can fly	40 (guess)	40 (guess)	40 (guess)	40 (guess)	40 (guess)	40 (guess)	20 (wild guess)	40 (wild guess)
Development cost, billion $	3.6 (guess)	5 (guess)	5 (guess)	5 (guess)	5 (guess)	5 (guess)	5 (wild guess)	5 (wild guess)
Unit cost of veh., million $	500 (wild guess)	500 (wild guess)	500 (wild guess)	500 (wild guess)	500 (wild guess)	500 (wild guess)	1,000 (wild guess)	500 (wild guess)
Years to develop	5 (wild guess)	5 (wild guess)	5 (wild guess)	5 (wild guess)	5 (wild guess)	5 (wild guess)	5 (wild guess)	5 (wild guess)

* This OTV must return a payload of 12.6/.7 = 18 MT of H2 to LLO for the lunar lander.

transfer tasks, not multipurpose OTVs. The aerobrake fraction numbers, which are of considerable significance in determining mass payback ratio, are uncertain. The aerobrake fraction is the percent of entry mass that is aerobrake. The LEO-GEO-LEO cryogenic vehicle is the first column in Table 4 is a point design for an OTV with some history. With one exception, all the rest of the aerobraked vehicles use an aerobrake fraction of 10 percent. This was chosen as an "optimistic" conservative number. An aerobrake fraction of 5 percent and zero boiloff were used for the cryogenic OTV that loads hydrogen in LEO and oxygen in LLO because these numbers were required to get positive mass payback ratios, or to get more back than was sent out. Figures 3 and 4 show concepts for such vehicles. Appendix A contains scaling plots for the cryogenic vehicles and other data.

Nuclear electric and solar sail OTVs were also included. These were not technically evaluated, designed, or costed in any detail. They serve here as examples of systems that might require little or no propellant however, and as such are limiting cases for mass payback analysis. The nuclear electric case represents a multi-megawatt electric vehicle. Low power (100 KW) electric propulsion vehicles have a hard time competing with cryogenic chemical propulsion. High power (MW) vehicles are much more competitive. It was assumed the electric propulsion vehicle could use oxygen as a working fluid, because production facilities for oxygen were already sized. In reality, oxygen is probably a poor choice, and some other lunar produceable propellant must be found. Future work should include a better definition of these vehicles.

The Earth launch of the inert mass of all the propellant carriers in Table 4 was not included in the mass payback analysis (presented in later tables), and probably should be

FIGURE 3 - OTV DEPARTING MOON WITH OXYGEN FOR LEO

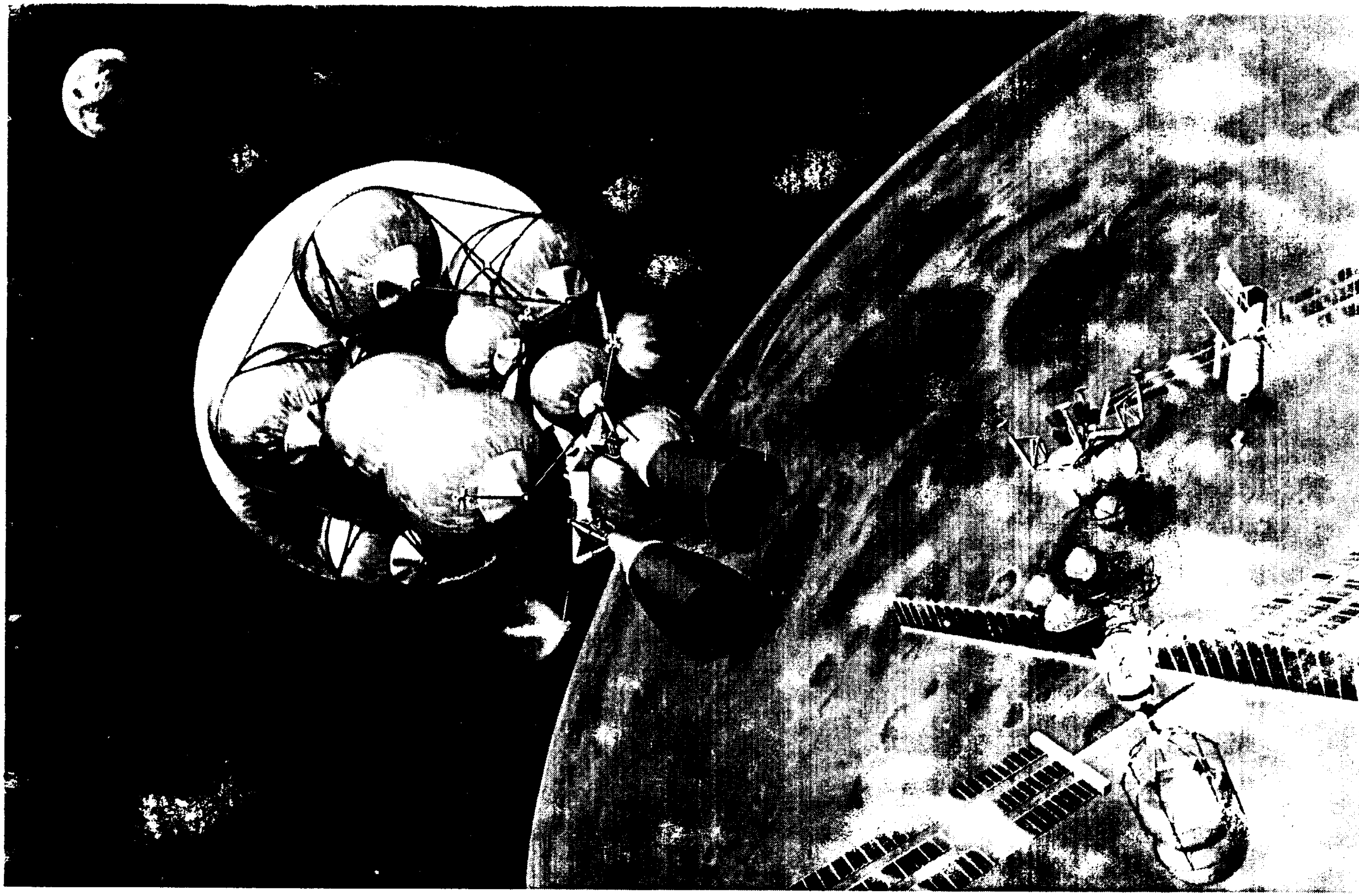
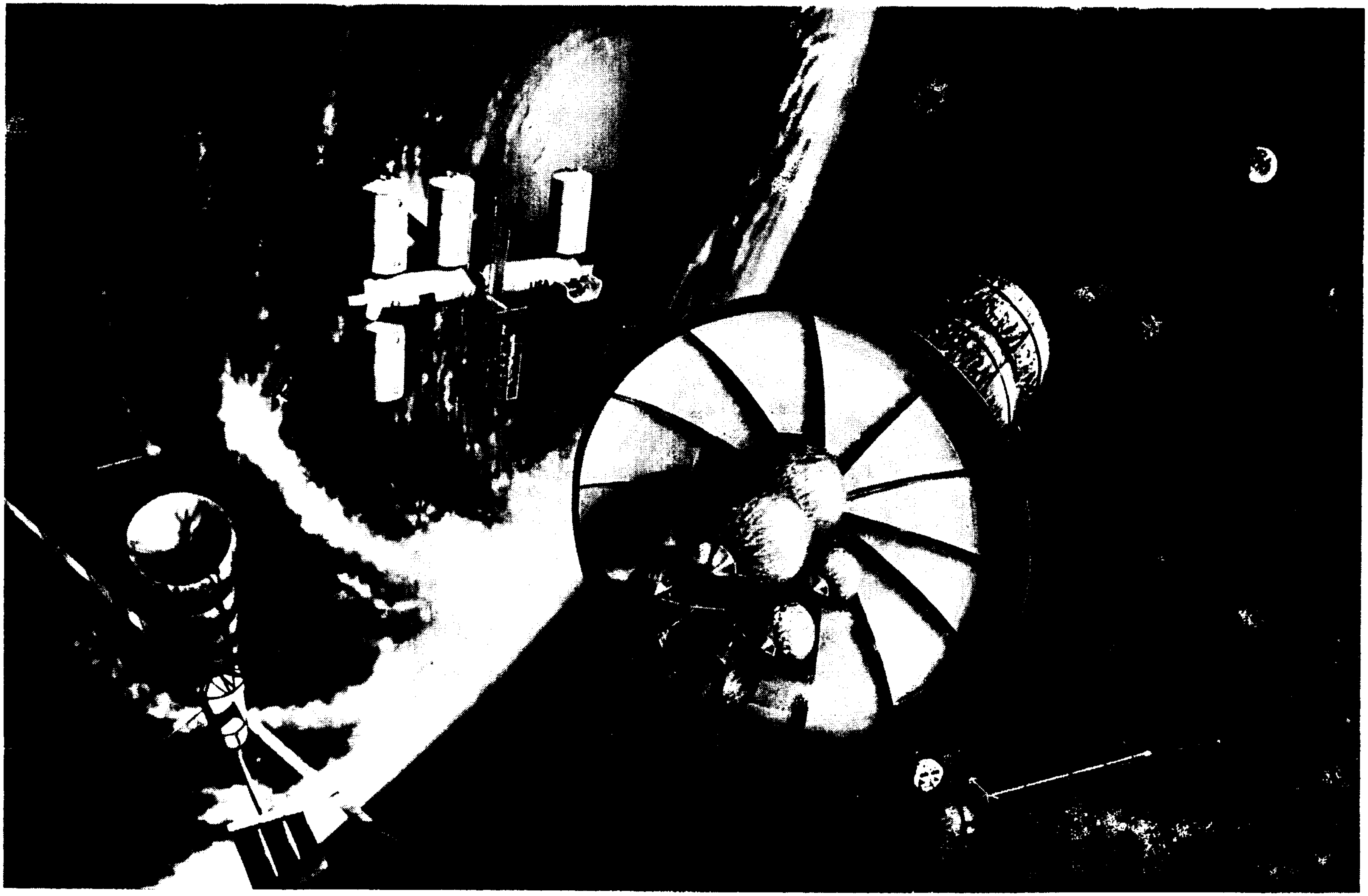


FIGURE 4 - OTV DEPARTING LEO WITH HYDROGEN FOR THE MOON



for the solar sail and electric systems. The solar sail and electric vehicles will require round trip times from LEO to lunar orbit on the order of six months to a year and a large number of these vehicles (10?) may therefore be required to service 1,000 MT/year LEO markets. Leaving out the difficulties associated with large numbers of these slow vehicles makes the overall costs appear artificially low.

Table 5 describes a much smaller OTV designed (by JSC) for LEO to GEO transport, and the landing of a lunar base. This design was assumed to carry all infrastructure to the lunar surface from LEO. This design (or something similar) may become operational in the 1995 time frame. Figure 5 shows the stack of two small OTVs with an expendable lander and a 17.5 MT payload destined for the lunar surface. Figure 6 shows a single small OTV returning with a manned capsule.

The operations cost estimate for this vehicle includes the unit (but not transport) cost of airframe replacement every 40 missions.

Table 6 describes three lander/launcher systems. The base and plants were all assumed to be landed with the expendable lander delivered by the two stage small OTV system. Figure 7 shows one of these landers on the surface with a base element. Manned ascent stages and other manned capsules were not sized or separately costed as parts of either the expendable or reusable lander systems but probably should be.

The reusable cryogenic lander is a key element here. Its estimated operations cost include airframe replacement, engine replacement, and maintenance. Its payload up to LLO is assumed to always be 43 MT regardless of where hydrogen is loaded. If hydrogen is

TABLE 5 - TWO STAGE SMALL OTV (BASE LANDER)

Space based, aerobraked, two identical stages load O_2 & H_2 in LEO. Mission is LEO-LLO-LEO. First stage drops off before LLO insertion.

Inert mass, MT (for one stage)	7
Start burn mass, MT (for entire stack)	133
Max. possible payload, MT	35 (to LLO)
Max. O_2 payload, MT (.95 x max.)	33.25
Max. H_2 payload, MT (.7 x max.)	24.5
Total Propellant Mass, MT (for total stack)	84
Mixture Ratio	7
O_2 Propellant, MT	73.5
H_2 Propellant, MT	10.5
One mission costs, K$ (ops and airframe amortization)	37,000
General payload transportation cost, $/Kg	1,057
O_2 transportation to LLO cost, $/Kg	1,113
H_2 transportation to LLO cost, $/Kg	1,510
Development cost, billion $	3.6 (guess)
One airframe unit cost, mil. $	500 (wild guess)
No. of missions one airframe can fly	40 (guess)

FIGURE 5 - STACK OF 2 SMALL OTVs WITH EXPENDABLE LANDER

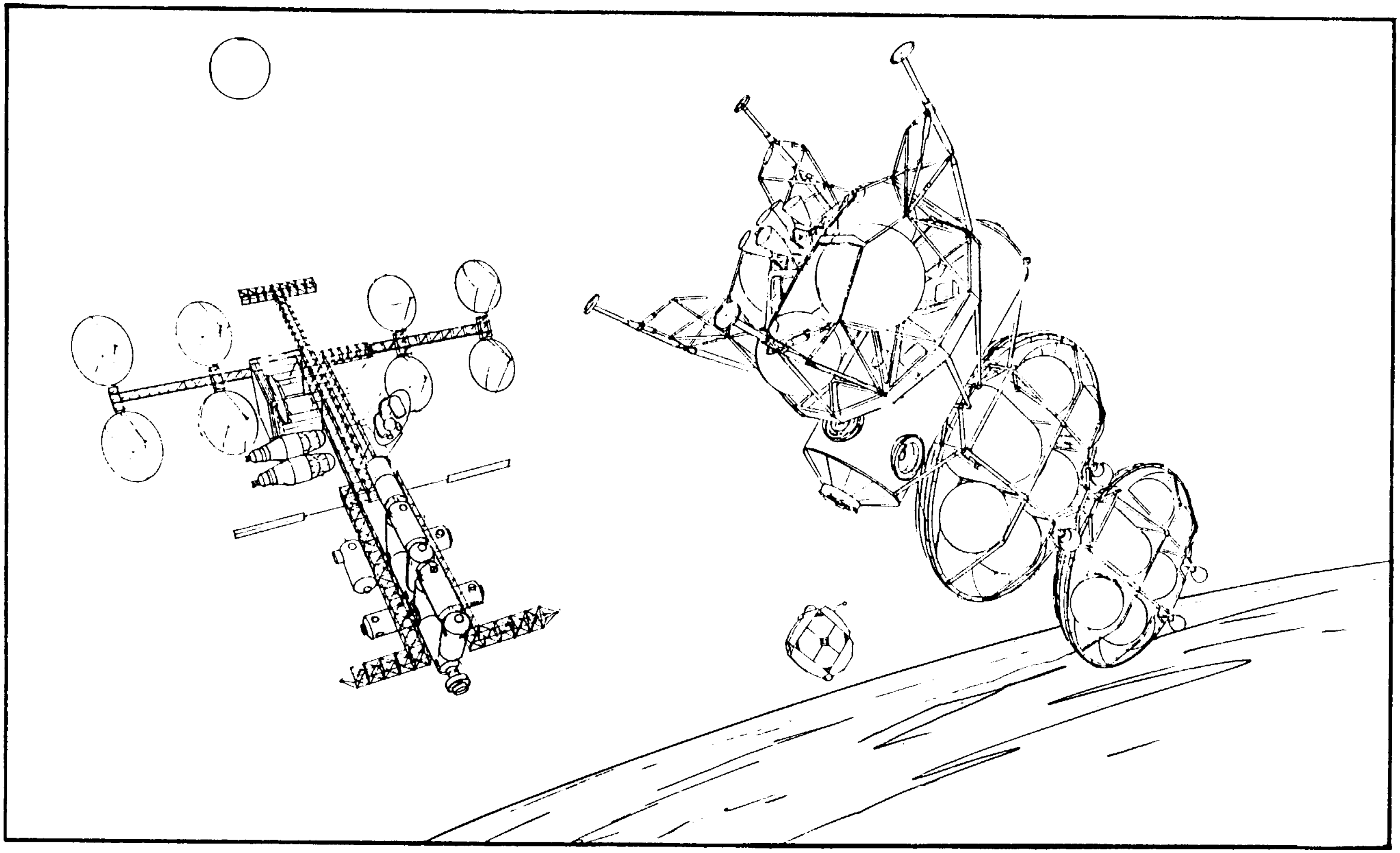


FIGURE 6 - SMALL OTV AEROBRAKING WITH A MANNED CAPSULE

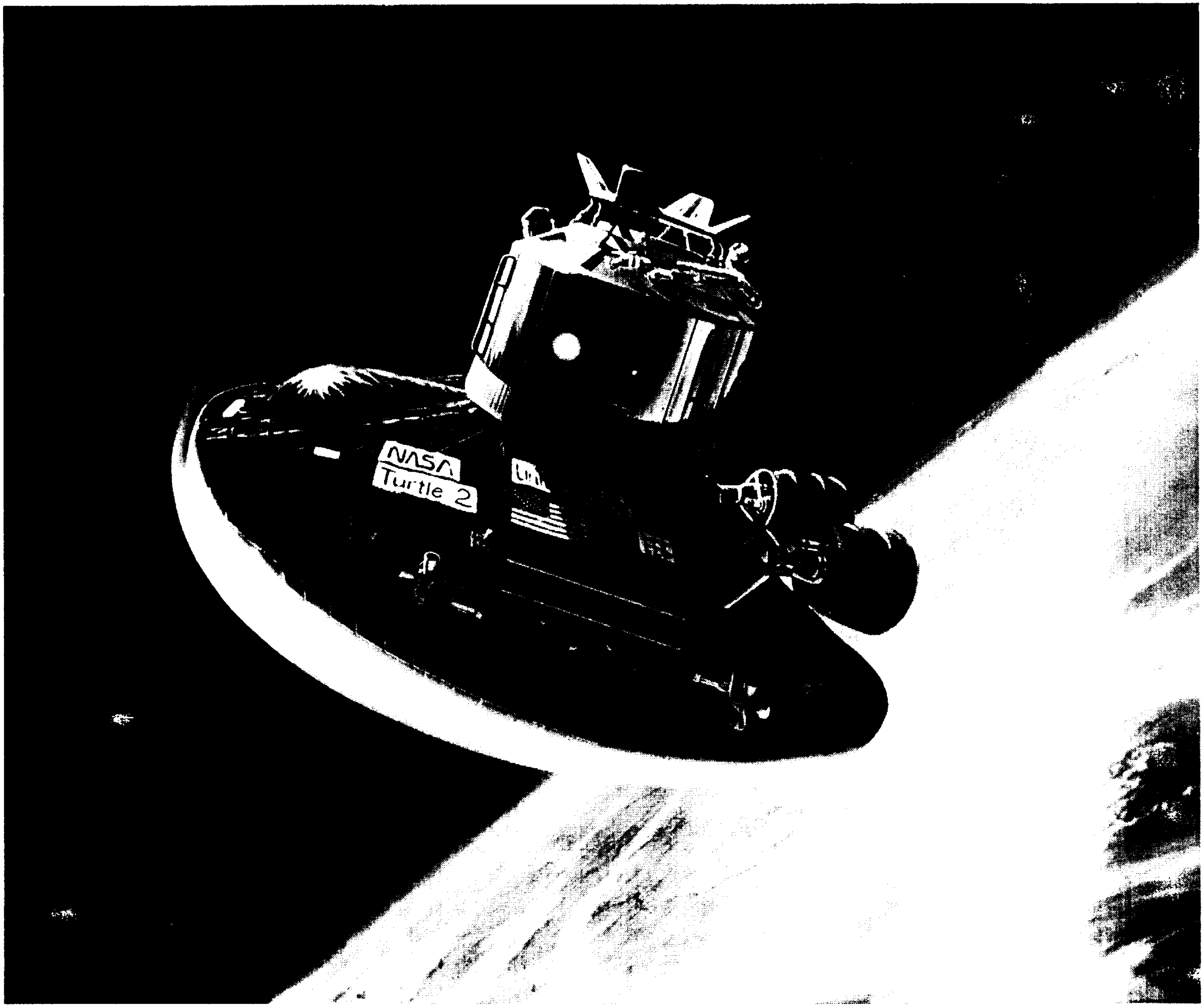
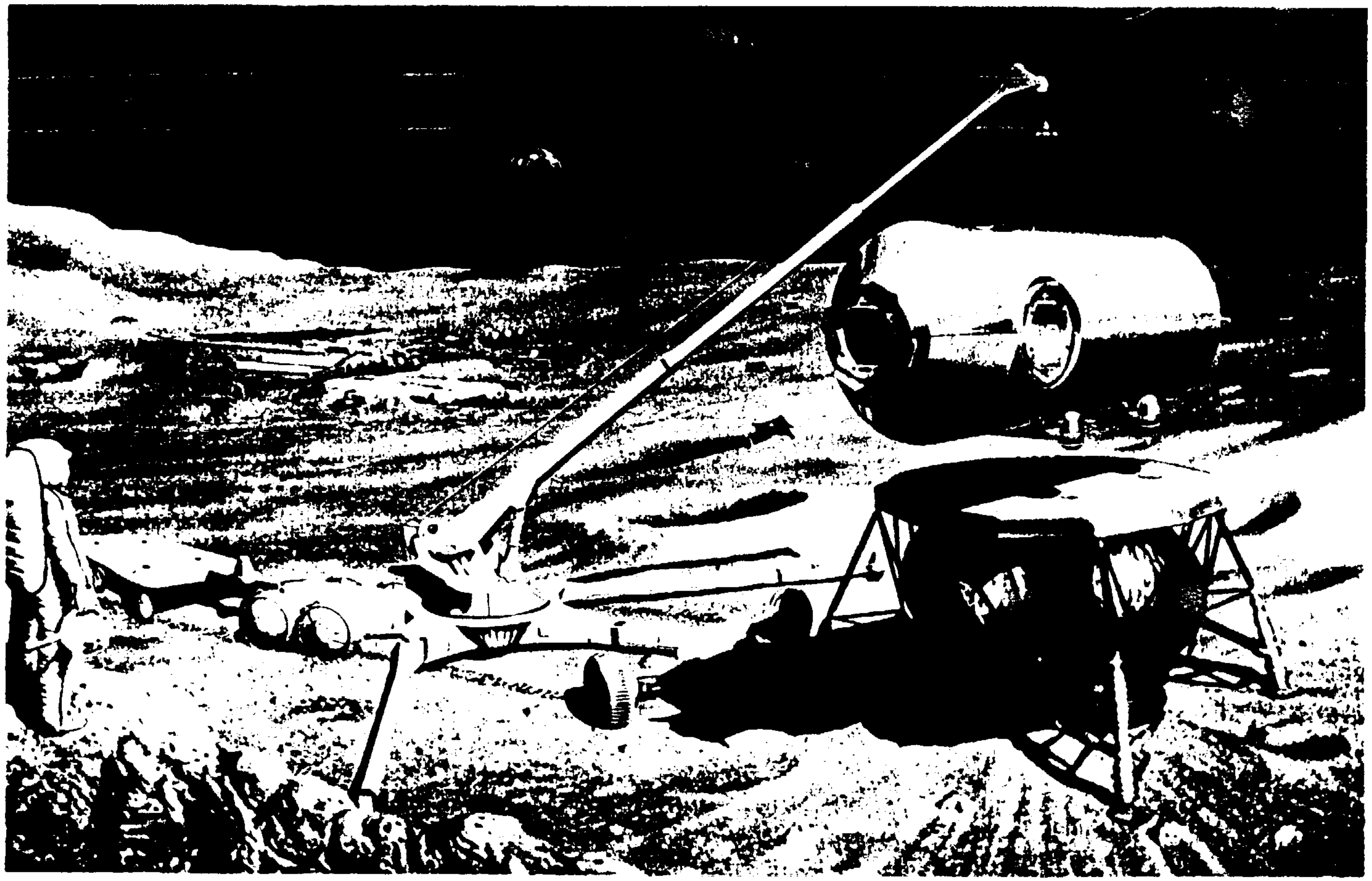


TABLE 6 - LUNAR LANDER/LAUNCHERS

	Expendable Cryogenic	Reusable Cryogenic LS based and fueled	Mass Driver (Numbers scaled from Ref.5)
Deorbit or launch mass, MT	34.9	78.2	1,500
Inert mass, MT	3.8	5.2	1,500
Max. payload up, MT	0	43 *(dwn empty)	2,000 (MT/year)
Max. payload dwn, MT	17.5	17.5 (up empty)	0
Total Propellant Mass, MT (for total stack)	13.6	30	0
Mixture Ratio	7	7	
O2 Propellant, MT	11.9	26.25	
H2 Propellant, MT	1.7	3.75	
No. engines	1	3	
Missions between overhaul or replacement	1	30	
New engine cost, K$		10,000 (guess)	
Manhours maintenance per mission		200 (wild guess)	
$/manhour, LS		50,000 (guess)	
Total airframe life (No. of missions)	1	500 (wild guess)	
Development cost, billion $	2 (guess)	2 (guess)	10 (guess)
Operations cost, per mission, K$ (includes airframe replacement, engine replacement, and maintenance)	92,000	12,500	
Unit cost, K$	75,000 (wild guess)	750,000 (wild guess)	1,897,500 (guess)

* Carries 38.2 MT up if H2 loaded in LLO, 26.7 up if H2 & O2 loaded in LLO.

FIGURE 7 - EXPENDABLE LANDER ON LUNAR SURFACE



loaded in LLO the actual payload up would be 38.2 MT. This results in some error for the oxygen only production case, but it is an optimistic error, and the end result for the oxygen only case is still not positive.

A mass driver was included, and assumed to transport mass from the LS to LLO. A catcher was not included but probably should be. The mass driver serves as an example of an advanced device that might use no propellants, but requires a large investment in surface infrastructure.

Tables 7 through 14 show the evaluation of a set of transportation schemes. They are based on a LEO oxygen market of approximately 1,400 MT/year (the "Total less SDI" market of Table 1) unless otherwise noted.

Table 7 computes three parameters of interest: the steady state best case mass payback ratio, the lunar launch ratio, and the lunar propellant production ratio. Some of these have been computed by several other authors and should not be controversial (References 3,4,7, and others). The steady state best case mass payback ratio is the inbound payload (oxygen) of a given mission over the hydrogen loaded in LEO for the OTV and for the lunar landers. The lunar launch ratio is the total propellants launched from LLO per OTV mission over the oxygen delivered to LEO per OTV mission. The lunar propellant production ratio is the total propellant produced on the lunar surface per OTV mission (including LEO delivered and OTV and Lander propellant) over the oxygen delivered to LEO per OTV mission. As expected the oxygen only case does the worst (col. 1) and the mass driver/solar sail does best (col. 7).

TABLE 7 - STEADY STATE MASS PAYBACK RATIO CALCULATIONS

	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
OTV delivered O2 to LEO, MT/flight	49.875	111.34	91.2	95	228	95	95
OTV O2 propellant req., MT/flight (load LLO, LLO-LEO-LLO)	87.5	87.5	87.5	0	59.85	0	0
OTV H2 propellant req., MT/flight	12.5 (load LEO)	12.5 (load LLO)	12.5 (load LEO)	0		0	0
Reus. lunar lander O2 del.to LLO, MT/flight (.95 x maximum payload)	40.85	40.85	1 (mass driv.)	40.85	40.85	40.85	0
No. of lunar lander flights req. per OTV flight	3.36	4.87	178.70	2.33	7.05	2.33	0
Lunar lander O2 prop. req., MT/flight (for one round trip)	26.25	26.25	0	26.25	26.25	26.25	0
Lunar lander H2 prop. req., MT/flight (for one round trip)	3.75	3.75	0	3.75	3.75	3.75	0
OTV H2 del. to LLO from Earth, MT/flight	12.61	0	0	8.72	26.42	0	0
Total payload, LEO to LLO, of OTV, MT (hydrogen plus tankage)	24.00	0	0	12.46	37.75	0	0
Steady state best case mass payback ratio (Total inbound payload/(outbound payload + OTV H2))	1.37	infinity	7.30	7.63	6.04	infinity	infinity
1/(steady state best case mass payback ratio)	0.73	0	0.14	0.13	0.17	0.00	0
Lunar launch ratio (Total propellants launched from LLO/O2 del. to LEO)	2.75	1.90	1.96	1.00	1.26	1.00	1
Lunar propellant production ratio (Total prop. produced/O2 delivered to LEO)	4.52	2.17	1.96	1.64	2.07	1.64	1

The first column in Table 7 assumes only oxygen production on the lunar surface. The OTV sized in the fourth column of Table 4 is then used for transport of oxygen to LEO and hydrogen back to the Moon. This OTV required a 5% of entry mass aerobrake and no boiloff to get the mass payback ratio positive. The reusable cryogenic lander from Table 6 is used.

The second column in Table 7 assumes hydrogen is available on the lunar surface. The OTV sized in column three of Table 4 and the reusable cryogenic lander are used.

The third column assumes a mass driver is used to launch propellants to LLO. The OTV in column five of Table 4 is used.

The fourth column uses the reusable lander to get to LLO and a solar sail OTV to transfer propellants back and forth from LEO. The solar sail may be unreasonably large, may have too long flight times (requiring too many vehicles) and may be unable to operate in low Earth orbit. All these factors were not analyzed. The solar sail is still worth considering, however, because it uses no propellant, and not considering the objections raised above, indicates what limit values may be. This may shed some light on what performance improvements in more conventional systems can do.

The fifth column in Table 7 assumes the reusable lander brings propellant to LLO which is then transferred to LEO with an electric propulsion (oxygen using) OTV. This OTV may also be unable to operate in LEO (due to nuclear safe altitude restrictions), may have too long flight times (requiring too many vehicles) and may not last for forty missions. All these factors were not analyzed.

The sixth column is the same as the fourth, except hydrogen is assumed available on the lunar surface.

The last column, all other objections to mass drivers and solar sails aside, is the best transportation system from a simple mass payback basis since it uses no propellants at all.

The last evaluation of the cases considered in Table 7 before costs must be included is an average mass payback ratio which is computed in Tables 8A and 8B. The average mass payback ratio is all the mass sent out from LEO including the surface base, plant mass, base and plant resupply, and life support resupply, over the propellant mass returned to LEO during the estimated system lifetime. The average mass payback ratio is a function of market size. Table 8A shows a small market, Table 8B a maximum projection. Key numbers include the number of base and plant personnel and the fraction of the base and plant mass that must be replaced every year. Based on the last row in this table, the average mass payback ratio, the oxygen only scheme with all cryo transportation could be thrown out. However, each of these cases is further evaluated in Tables 9-13. Future work should include sensitivity studies to the variables mentioned above.

Table 9 estimates the transportation cost to place the base and plants. It is assumed one large SDV launch (100 MT payload) and 1.5 Shuttle launches (of men and payload) are required to support a two stage small OTV and expendable lander mission launched from LEO. The entire initial base and plant mass is assumed to be placed in this manner. Another less costly possibility would be to use the large SDV or the larger HLLV to launch all

TABLE 8A - AVE. MASS PAYBACK RATIO CALCULATIONS

O2 LEO MARKET = 1,357 MT/year	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
System lifetime, years	20	20	20	20	20	20	20
O2 LEO Market, MT/year	1,357	1,357	1,357	1,357	1,357	1,357	1,357
H2 LEO market, MT/year	194	194	194	194	194	194	194
Base mass, MT	87.5	87.5	87.5	87.5	87.5	87.5	87.5
Annual O2 plant production, MT/year	6,140	2,942	2,659	2,229	2,814	2,229	1,357
MT H2 prod. req./MT O2 del. to LEO	0	0.28				0.09	0
Annual H2 plant production, MT/year	0	375				125	0
O2 Plant multiplier,plant mass/annual prod.	0.20	0.24	0.25	0.26	0.24	0.26	0.29
H2 Plant multiplier,plant mass/annual prod.		1.00				1.00	
O2 plant mass, MT	1,228	706	655	574	683	574	395
H2 plant mass, MT	0	375	0	0	0	125	0
Total base & plant, MT	1,315	1,169	742	661	771	786	482
Fraction of base and plant mass that must be resupplied each year	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Annual base and plant resupply, MT/year	26	23	15	13	15	16	10
No. base and plant personnel	23 (guess)	18 (guess)	16 (guess)	15 (guess)	16 (guess)	16 (guess)	13 (guess)
Life support resupply, MT/person-year (estimate based on water & O2 recycling)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Annual life support resupply, MT/year	25	20	17	16	18	17	14
Total mass on LS for plant & life support resupply over lifetime of plant, MT	1,026	868	644	592	662	656	482
Base placement system, mass in LEO over mass del. to LS	6.8	6.8	6.8	6.8	6.8	6.8	6.8
*Total base and plant mass and all resupply LEO mass charge for system life,MT	9,971	8,815	5,691	5,087	5,903	5,998	3,763
Steady state MT from Earth/MT del. to LEO 1/SS MPBR	0.73	0.00	0.14	0.13	0.17	0.00	0.00
Total LEO market for plant lifetime	122,794	58,830	53,180	44,581	56,284	44,581	27,141
Ave. mass payback ratio = total lifetime LEO market/(Total LEO charge for base, plant, and all resupply mass + (1/SS MPBR) x(Total LEO market for plant lifetime))	1.23	6.67	4.10	4.08	3.70	7.43	7.21

* LS base and plant(s) mass are multiplied by a factor of 6.8 to get this number. Resupply mass is not multiplied by a factor and is therefore a best case number.

TABLE 8B - AVE. MASS PAYBACK RATIO CALCULATIONS

O2 LEO MARKET = 4,316 MT/year	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
System lifetime, years	20	20	20	20	20	20	20
O2 LEO Market, MT/year	4,316	4,316	4,316	4,316	4,316	4,316	4,316
H2 LEO market, MT/year	617	617	617	617	617	617	617
Base mass, MT	87.5	87.5	87.5	87.5	87.5	87.5	87.5
Annual O2 plant production, MT/year	19,527	9,355	8,457	7,089	8,950	7,089	4,316
MT H2 prod. req./MT O2 del. to LEO	0	0.28				0.09	0
Annual H2 plant production, MT/year	0	1,192				396	0
O2 Plant multiplier,plant mass/annual prod.	0.15	0.18	0.18	0.19	0.18	0.19	0.22
H2 Plant multiplier,plant mass/annual prod.		1.00				1.00	
O2 plant mass, MT	2,929	1,685	1,562	1,368	1,630	1,368	942
H2 plant mass, MT	0	1,192	0	0	0	396	0
Total base & plant, MT	3,017	2,965	1,649	1,456	1,717	1,852	1,030
Fraction of base and plant mass that must be resupplied each year	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Annual base and plant resupply, MT/year	60	59	33	29	34	37	21
No. base and plant personnel	49 (guess)	35 (guess)	27 (guess)	25 (guess)	28 (guess)	27 (guess)	19 (guess)
Life support resupply, MT/person-year (estimate based on water & O2 recycling)	1.1	1.1	1.1	1.1	1.1	1.1	1.1
Annual life support resupply, MT/year	54	39	30	27	31	29	21
Total mass on LS for plant & life support resupply over lifetime of plant, MT	2,295	1,958	1,262	1,124	1,310	1,326	831
Base placement system, mass in LEO over mass del. to LS	6.8	6.8	6.8	6.8	6.8	6.8	6.8
*Total base and plant mass and all resupply LEO mass charge for system life,MT	22,809	22,118	12,478	11,022	12,989	13,918	7,834
Steady state MT from Earth/MT del. to LEO 1/SS MPBR	0.73	0.00	0.14	0.13	0.17	0.00	0.00
Total LEO market for plant lifetime	390,541	187,107	169,138	141,789	179,008	141,789	86,320
Ave. mass payback ratio = total lifetime LEO market/(Total LEO charge for base, plant, and all resupply mass + (1/SS MPBR) x(Total LEO market for plant lifetime))	1.27	8.46	4.74	4.79	4.20	10.19	11.02

* LS base and plant(s) mass are multiplied by a factor of 6.8 to get this number. Resupply mass is not multiplied by a factor and is therefore a best case number.

TABLE 9 - BASE PLACEMENT TRANSPORTATION COST

ANNUAL LEO O2 MARKET (MT) = 1,357	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
Support base mass, MT	87.5	87.5	87.5	87.5	87.5	87.5	87.5
Annual O2 plant production, MT/year	6,140	2,942	2,659	2,229	2,814	2,229	1,357
O2 plant size, MT	1,228	706	655	574	683	574	395
Annual H2 plant production, MT/year	0	375	0	0	0	125	0
H2 plant size, MT	0	375	0	0	0	125	0
Mass driver, MT	0	0	1,500	0	0	0	1500
Total mass on lunar surface, MT	1,315	1,169	2,242	661	771	786	1,982
MT one lunar lander mission can place on LS	17.5	17.5	17.5	17.5	17.5	17.5	17.5
No. of missions req. to place base & plants	75	67	128	38	44	45	113
Mass in LEO of one mission, MT	119	119	119	119	119	119	119
Shuttle flights req. to support one mission	1.5	1.5	1.5	1.5	1.5	1.5	1.5
SDV flights req. to support one mission	1	1	1	1	1	1	1
Cost per Shuttle flight, million $	114	114	114	114	114	114	114
Cost per SDV flight, million $	134	134	134	134	134	134	134
Total Earth surface to LEO cost to support one lunar surface mission, million $	305	305	305	305	305	305	305
Ave. Earth surface to LEO cost, $/KG	2,218	2,218	2,218	2,218	2,218	2,218	2,218
OTV operations cost/mission, million $	37	37	37	37	37	37	37
Expendable lander cost/mission, million $	92	92	92	92	92	92	92
Total LEO to LS cost per mission, million $	129	129	129	129	129	129	129
Total LEO to LS cost per KG, $/KG	7,371	7,371	7,371	7,371	7,371	7,371	7,371
Total cost to place base and plants, million $	32,623	28,984	55,609	16,393	19,116	19,483	49,166
$/KG, Earth surface to lunar surface	24,800	24,800	24,800	24,800	24,800	24,800	24,800
Max. possible number of devoted Shuttle missions per year	24	24	24	24	24	24	24
No. of years required to place base & plant	4.70	4.17	8.01	2.36	2.75	2.81	7.08

lunar base/plant elements to LEO. The base and plant placement costs (many 10s of billions) are large numbers in the overall analysis primarily because all OTV base lander missions are assumed to take place before any lunar propellant production is available. The number of operations required is significant also. Either a long time or significant additions to KSC and the Space Station (an additional Space Station?) may be required. These costs are not included in this or following tables.

The last row in Table 9 shows the time needed to place the base assuming the maximum possible number of devoted Shuttle flights per year in the next to last row. The long times needed, and the many Shuttle flights required indicate the Earth launch transportation scenario (approx. 2/3 of the mass lifted by SDV, 1/3 by Shuttle) may be unreasonable. The SDV or other heavy lift launch vehicle used for the majority of the mass is assumed to be inexpensive and not man-rated in many studies however. Many Shuttle flights or flights of some later generation man-rated vehicle will be required, even if all the propellants and hardware are lifted by the SDV. This may be the limiting factor on construction of such a base if it is to be done in the near term.

Table 10 computes the operations cost to deliver propellants. Development costs are not included (assumed to be zero). From a comparison of the last row showing these costs with the large SDV operations cost to launch oxygen to LEO which is assumed to be in the range of \$1,500 \$/kg, the oxygen only case with conventional cryo propulsion can be eliminated as uneconomical. Proponents of this scheme may wish to critically examine the OTV and reusable lander operations costs. Future work should include a sensitivity study

TABLE 10 - PROPELLANT DELIVERY TRANSPORTATION COST CALCULATIONS

	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
MT del. to LEO per one OTV mission	50	111	96	95	228	95	95
OTV operational cost per mission (round trip), million $	19	19	18.5	18.5	56	18.5	18.5
$/KG, LLO to LEO	371	166	193	195	246	195	195
MT payload of reusable lander	43	43		43	43	43	
No. of reusable lunar lander missions per OTV mission	3.36	4.87		2.33	7.05	2.33	
Reusable lunar lander operational cost per mission, million $	12.50	12.50		12.5	12.5	12.5	
$/KG, Lunar surface to LLO	291	291	0	291	291	291	0
Total lander operations cost per OTV mission, million $	42.04	60.84	0.00	29.07	88.08	29.07	
Steady state best case mass payback ratio (total inbound payload/(outbound payload + OTV H2))	1.37	infinity	7.30	7.63	6.04	infinity	infinity
No. large SDV missions per OTV mission (70 MT H2 per SDV mission)	0.36	0.00	0.18	0.12	0.38	0.00	0.00
SDV launch costs/OTV mission, million $ (134 million $ per SDV launch)	48.07		23.93	16.69	50.58	0.00	0.00
Total operations cost per OTV mission including lander missions, million $	108.61	79.34	42.43	64.26	194.67	47.57	18.50
$/KG, Lunar surface to LEO	2,178	713	442	676	854	501	195

on SDV operations cost.

Table 11 summarizes the operations costs for two periods. The base and plant placement costs before lunar propellant production begins as determined in Table 9 is given in the upper section. The operating cost after the lunar plant and base are established (ie. the propellant transportation costs from Table 10, the resupply costs from Table 8A, and the base and plant operations costs from Table 2) is given in the lower section.

Table 12 summarizes the development costs for the vehicles, plants and base proposed by each scheme.

Tables 13A and 13B (for LEO oxygen markets of 1,357 and 4,316 MT/year) sums all the costs and divides them by the total market for the system life. The system life assumption of 20 years, after which all hardware will be worn out or obsolete, might be worth further examination. The bottom two lines show the $/kg for each case versus the estimate for a large SDV. Development costs for the common vehicles/elements in these transport schemes are not included as noted in the tables. On the basis of the bottom two sets of numbers delivery of oxygen to LEO can be dismissed as uneconomical for the approximately 1,400 MT/year market size.

Admittedly, the confidence in the accuracy of some cost estimates is not high, however in their defense, an analysis of this scope cannot include all costs, so they are more likely to be in error low than too high. The totals for the small market (third row from the bottom) range from 117 to 53 billion dollars depending on the transport scheme. Given that Apollo cost 74 billion dollars (1985 dollars), these total costs seem low.

TABLE 11 - OPERATIONS COST SUMMARY

ANNUAL LEO O2 MARKET (MT) = 1,357	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
BASE PLACEMENT ERA (before lunar propellant production begins)							
Total lunar surface mass, MT	1,315	1,169	2,242	661	771	786	1,982
$/KG, Earth surface to lunar surface	24,800	24,800	24,800	24,800	24,800	24,800	24,800
Billion $ transport cost for infrastructure	33	29	56	16	19	19	49
PROPELLANT PRODUCTION ERA (after lunar base & plant placed)							
O2 del. per year to LEO, MT/year	1,357	1,357	1,357	1,357	1,357	1,357	1,357
$/KG, lunar surface to LEO	2,178	713	442	676	854	501	195
Total annual O2 transport cost, million $/year	2,955	967	600	918	1,159	680	264
Annual mass del. to LS for plant & life support resupply, MT/year	51	43	32	30	33	33	24
Resupply $/KG, Earth surface to lunar surf. (Earth surface to LEO - large SDV $/KG, plus LEO to LS, prop. transfer $/KG)	3,518	2,053	1,782	2,016	2,194	1,841	1,535
Annual resupply cost, million $/year	180	89	57	60	73	60	37
Base and plant operations costs, million $/year	200	300	200	200	200	300	200
Total annual ops. cost, prop. prod. era, million $/year	3,335	1,356	857	1,178	1,431	1,040	501

TABLE 12 - DEVELOPMENT COSTS

ANNUAL LEO O2 MARKET (MT) = 1,357	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
Min. surf. base dev., billion $	5.00	5.00	5.00	5.00	5.00	5.00	5.00
O2 plant dev., billion $	6.14	2.94	1.99	1.67	2.11	1.67	1.02
H2 plant dev., billion $	0.00	1.87	0.00	0.00	0.00	1.87	0.00
Base lander OTV dev., billion $	3.6	3.6	3.6	3.6	3.6	3.6	3.6
Expendable lunar lander dev., billion $	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Reusable lunar lander dev., billion $	2.00	2.00	2.00	2.00	2.00	2.00	2.00
Propellant carrier OTV dev., billion $	5.00	5.00	5.00	0.00	5.00	0.00	0.00
Mass driver dev., billion $	0.00	0.00	10.00	0.00	0.00	0.00	10.00
Elec. prop. dev., billion $	0.00	0.00	0.00	0.00	5.00	0.00	0.00
Prop. carrier solar sail dev., billion $	0.00	0.00	0.00	5.00	0.00	5.00	5.00
Large SDV dev. cost, billion $	3.50	3.50	3.50	3.50	3.50	3.50	3.50
Total dev., billion $	27.24	25.92	33.09	22.77	28.21	24.65	32.12
Total dev. less large SDV, base lander OTV, and 50% of min. surf. base costs, billion $	17.64	16.32	23.49	13.17	18.61	15.05	22.52

TABLE 13A - SIMPLE COST COMPARISON

LEO MARKET 1,357 MT/YEAR (LEO ops plus manned Mars)	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
System life, years	20	20	20	20	20	20	20
Total O2 del. to LEO in system lifetime, MT	27,141	27,141	27,141	27,141	27,141	27,141	27,141
Total dev. less large SDV, base lander OTV, and 50% of min. surf. base costs, billion $	18	16	23	13	19	15	23
Billion $ transport cost for infrastructure	33	29	56	16	19	19	49
Total ops. cost for system lifetime, includes prop. transport, resupply, and plant and base ops., billion $	67	27	17	24	29	21	10
Total dev., ops, and initial transport cost for system life, billion $	117	72	96	53	66	55	82
Total costs/total prop. del. to LEO in system lifetime, $/KG	4,310	2,668	3,546	1,957	2,445	2,038	3,011
Large SDV cost for LEO del. of O2, $/KG (Operations only)	1,411	1,411	1,411	1,411	1,411	1,411	1,411

TABLE 13B - SIMPLE COST COMPARISON

LEO MARKET 4,316 MT/YEAR	O2 produc. only, all cyogenic propulsion	O2 & H2 prod., all cryogenic propulsion	O2 prod. only, mass driv.to LLO, cryo to LEO	O2 prod. only, cryo to LLO,sol. sail to LEO	O2 prod. only, cryo to LLO, elec.to LEO	O2 & H2 prod., cryo to LLO,sol. sail to LEO	Mass driv. to LLO, solar sail to LEO
System life, years	20	20	20	20	20	20	20
Total O2 del. to LEO in system lifetime, MT	86,320	86,320	86,320	86,320	86,320	86,320	86,320
Total dev. less large SDV, base lander OTV, and 50% of min. surf. base costs, billion $	18	16	28	17	23	19	25
Billion $ transport cost for infrastructure	75	74	78	36	43	46	63
Total ops. cost for system lifetime, includes prop. transport, resupply, and plant and base ops., billion $	200	72	44	65	81	52	22
Total dev., ops, and initial transport cost for system life, billion $	292	161	150	118	146	116	110
Total costs/total prop. del. to LEO in system lifetime, $/KG	3,388	1,869	1,742	1,362	1,696	1,347	1,269
Large SDV cost for LEO del. of O2, $/KG (Operations only)	1,411	1,411	1,411	1,411	1,411	1,411	1,411

The program was run again with a larger LEO market such as might occur with a large SDI program. Table 13B (LEO market - 4,316 MT/year) shows the $/kg costs for lunar propellant approaching or going below the 1,500 $/kg SDV number in all cases except the oxygen only conventional propellant case. This indicates that for a sufficiently large market lunar produced propellants might become viable for some transportation schemes. A large heavy lift launch vehicle designed for propellant delivery might run the cost from the Earth surface to LEO down to 700 $/kg. The program needs to be run again using this vehicle as the only Earth launcher, because Earth launch costs are a significant part of the lunar propellant costs also. However, the low HLLV propellant delivery costs would then compete directly against lunar propellant production.

If a reasonable design had gotten through the Table 13 "filter", a present value/cash flow analysis such as shown in Tables 14A and 14B would determine the time value of the scheme. Two versions of Table 14 are shown for the 1,357 MT/year market, all conventional propulsion with lunar oxygen and hydrogen both available. The first case (14A) has an initial investment of 45.3 billion, with an all negative number outcome. The second (14B) assumes the government picks up all costs except the last billion. The second case shows some positive numbers. Increasing the market to 4,316 MT/year and assuming the goverment picks up all but the last billion results in a healthy profit. All cases assume all initial investment is made in one year and production starts the next year. In reality, production is probably 10 to 15 years after project start.

It would be interesting to try this type of analysis on historical problems of resource

TABLE 14A - PRESENT VALUE/CASH FLOW ANALYSIS, ALL CRYO TRANSPORT, LUNAR O2 & H2

(all numbers millions of $ unless otherwise indicated)

End of year		0	1	2	3	4	5	19	20
Capital loan balance		45,300	43,035	40,770	38,505	36,240	33,975	2,265	0
Sales @ lg SDV cst & (assume inflation is	1,357 MT/yr O2 mkt 4%)		1,914	1,991	2,070	2,153	2,239	3,878	4,033
Expenses - capital repayment		0	(2,265)	(2,265)	(2,265)	(2,265)	(2,265)	(2,265)	(2,265)
Expenses - real $ (millions) ops.$ w/ inflation @	4%	0	(1,356)	(1,410)	(1,467)	(1,525)	(1,586)	(2,747)	(2,857)
Earnings before interest			(1,707)	(1,685)	(1,661)	(1,637)	(1,612)	(1,135)	(1,089)
Interest expense @	10%	0	(4,530)	(4,303)	(4,077)	(3,850)	(3,624)	(453)	(226)
Earnings after interest			(6,237)	(5,988)	(5,738)	(5,488)	(5,236)	(1,588)	(1,316)
Total cash flow		45,300	(6,237)	(5,988)	(5,738)	(5,488)	(5,236)	(1,588)	(1,316)
Present value of cash flows @		15.00%	(5,423)	(4,528)	(3,773)	(3,138)	(2,603)	(112)	(80)
Present value for years 1-20 @		15.00%	(27,040)						
Net Present value of project @		15.00%	(72,340)						

TABLE 14B - PRESENT VALUE/CASH FLOW ANALYSIS, ALL CRYO TRANSPORT, LUNAR O2 & H2

(all numbers millions of $ unless otherwise indicated)

End of year		0	1	2	3	4	5	19	20
Capital loan balance		1,000	950	900	850	800	750	50	0
Sales @ lg SDV cst & (assume inflation is	1,357 MT/yr O2 mkt 4%)		1,914	1,991	2,070	2,153	2,239	3,878	4,033
Expenses - capital repayment		0	(50)	(50)	(50)	(50)	(50)	(50)	(50)
Expenses - real $ (millions) ops.$ w/ inflation @	4%	0	(1,356)	(1,410)	(1,467)	(1,525)	(1,586)	(2,747)	(2,857)
Earnings before interest			508	530	554	578	603	(1,080)	1,126
Interest expense @	10%	0	(100)	(95)	(90)	(85)	(80)	(10)	(5)
Earnings after interest			408	435	464	493	523	1,070	1,121
Total cash flow		1,000	408	435	464	493	523	1,070	1,121
Present value of cash flows @		15.00%	355	329	305	282	260	75	68
Present value for years 1-20 @		15.00%	2,549						
Net Present value of project @		15.00%	1,549						

development (where all the numbers are available) such as offshore oil, or the American West to see if our scope is broad enough.

References

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5. Space Settlements, A Design Study, NASA SP413.
6. Personal communication from Dr. Andrew Cutler, Calspace, Univ. of California at San Diego.
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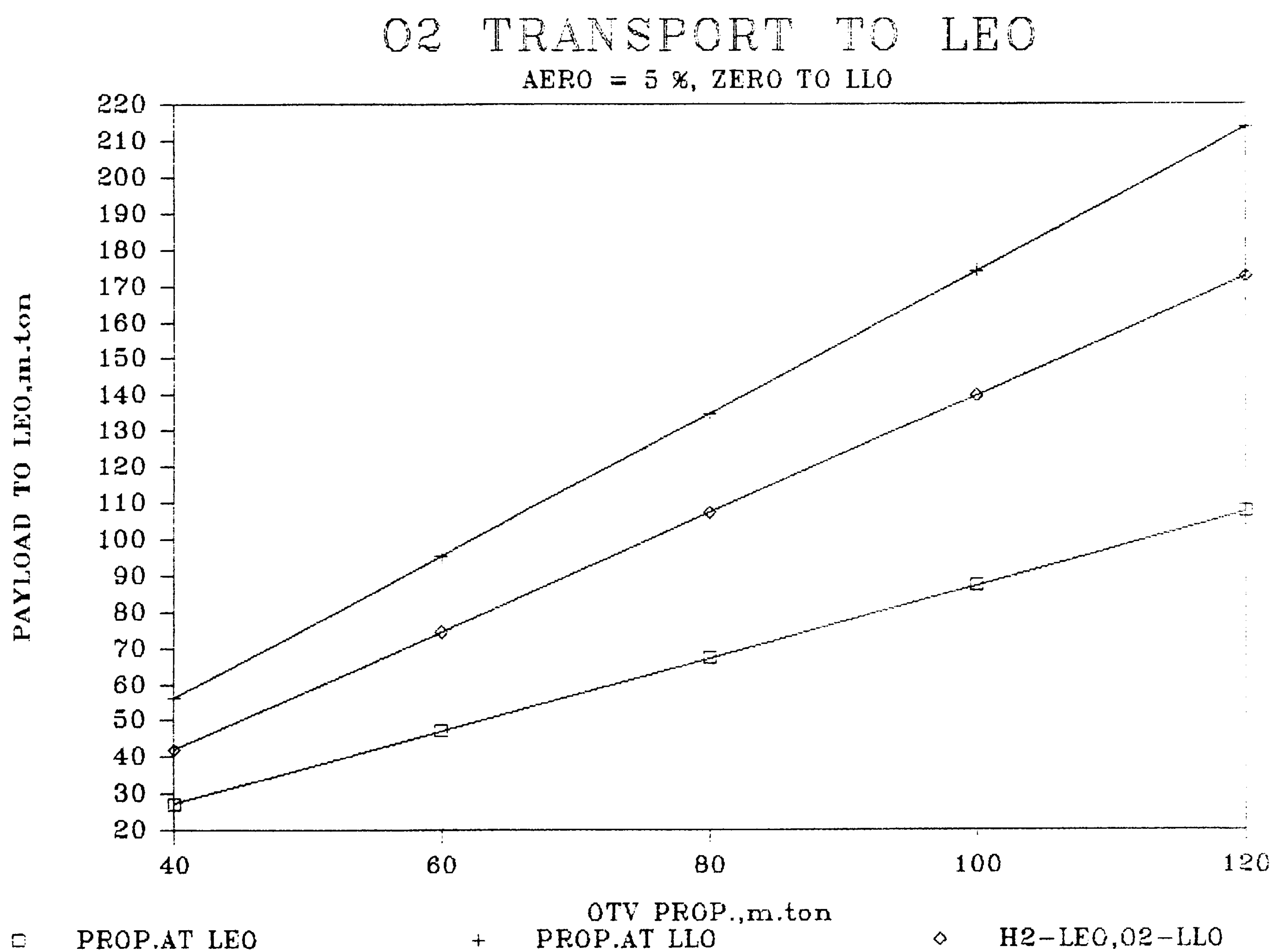
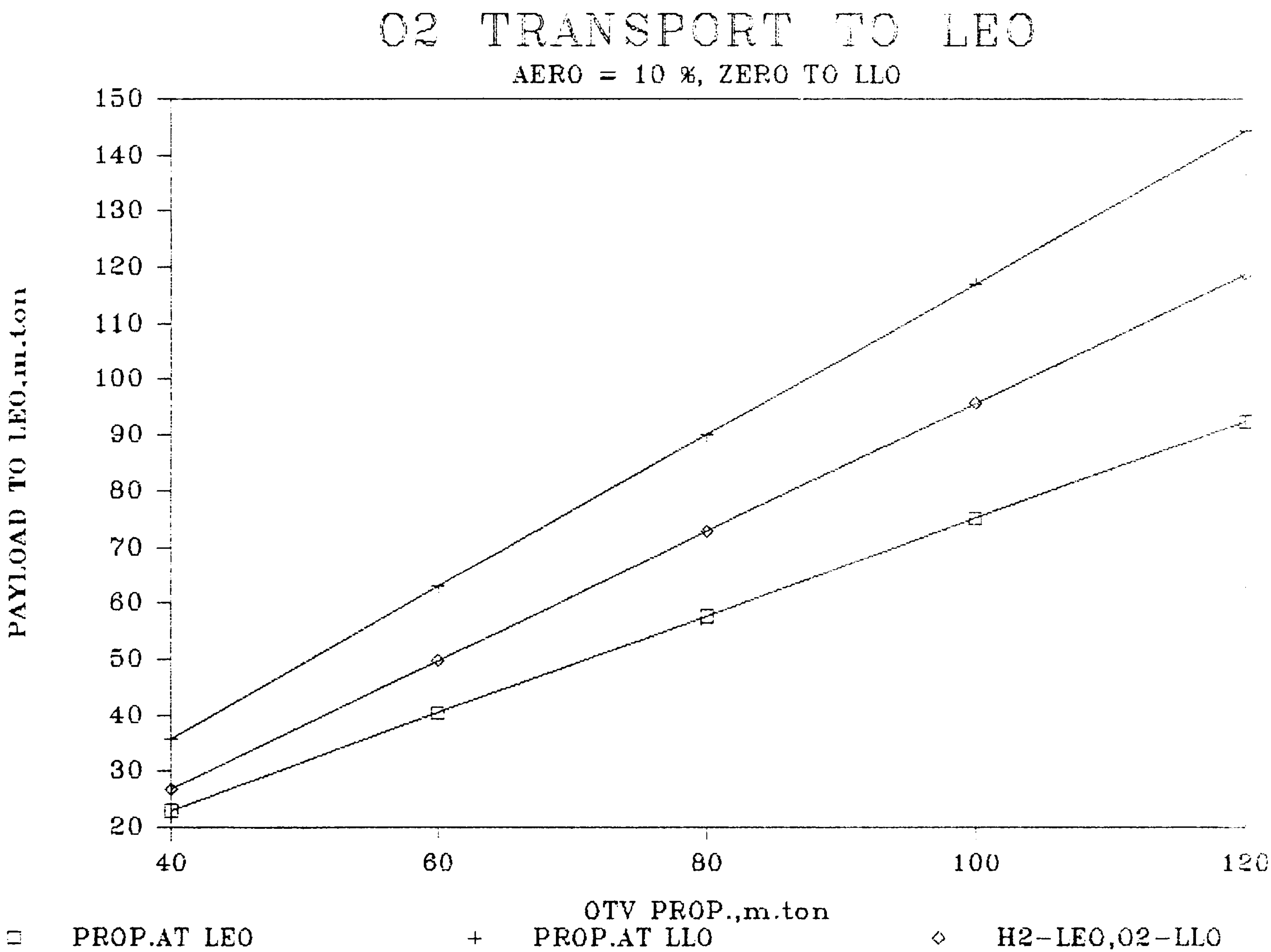
Appendix A

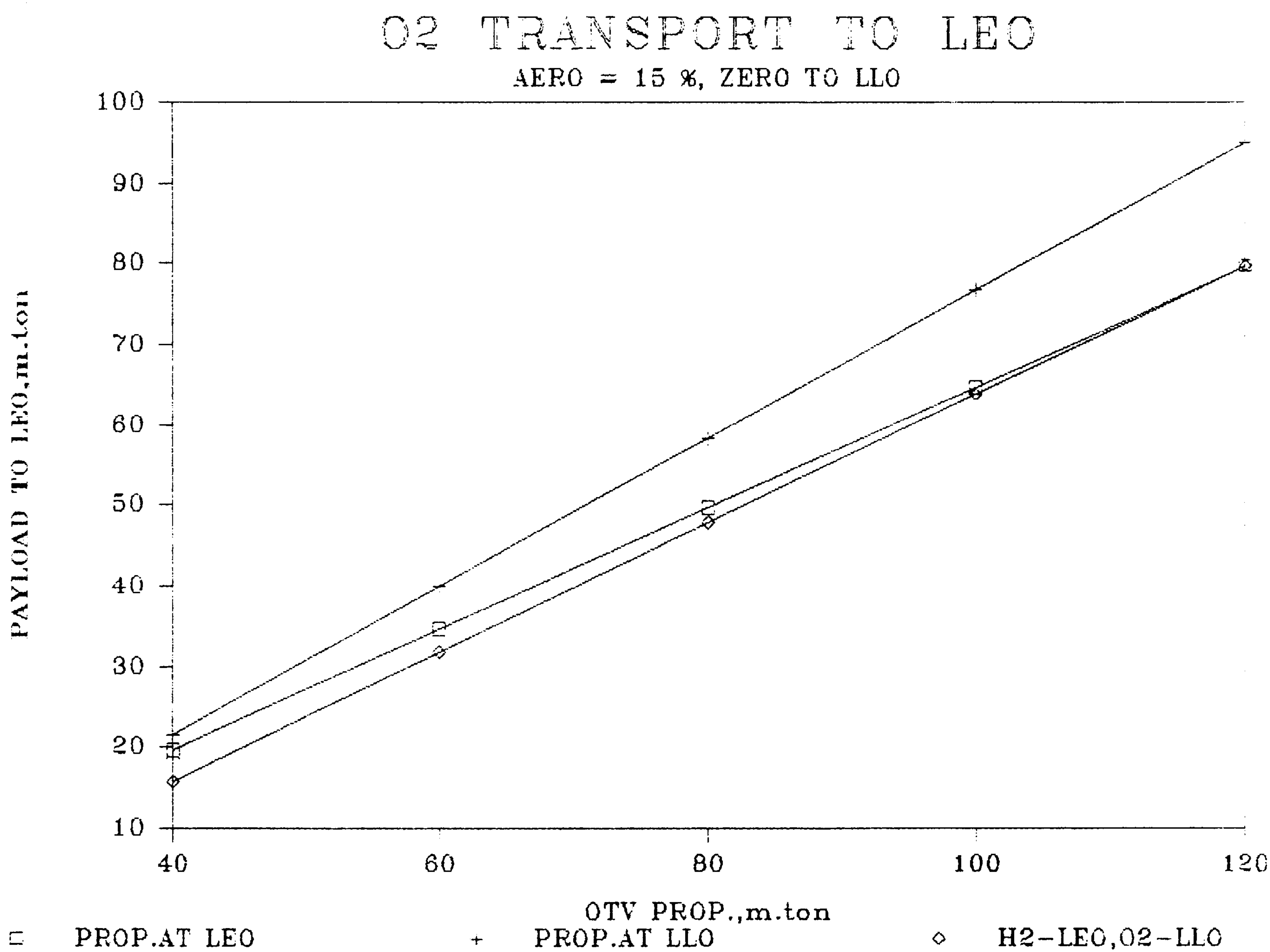
OTV Plots - Oxygen Transport to LEO

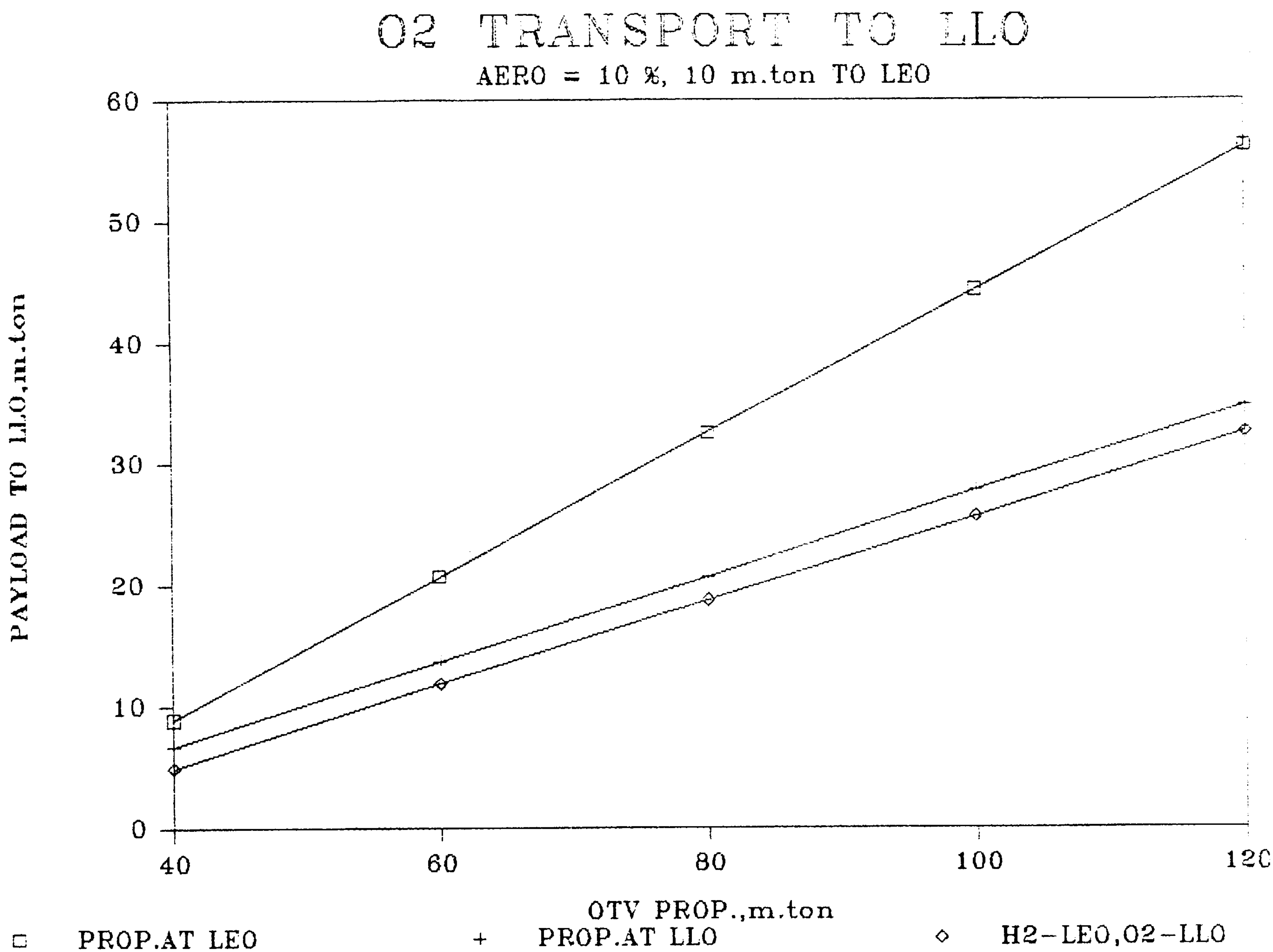
The following series of plots provide scaling data for OTV size selection. A boiloff of .2 MT/day for propellants in the vehicle tanks only is assumed. LEO is defined as 500 km and LLO as 200 km. The return aerobraking maneuver is targeted to an apogee 150 km above the Space Station (resultant Earth orbit 25 x 650 km). The vehicle then circularizes at 650 km and waits for the correct phasing to begin the rendezvous sequence. An effective specific impulse of 460 seconds was assumed for all vehicles. The following delta Vs were used.

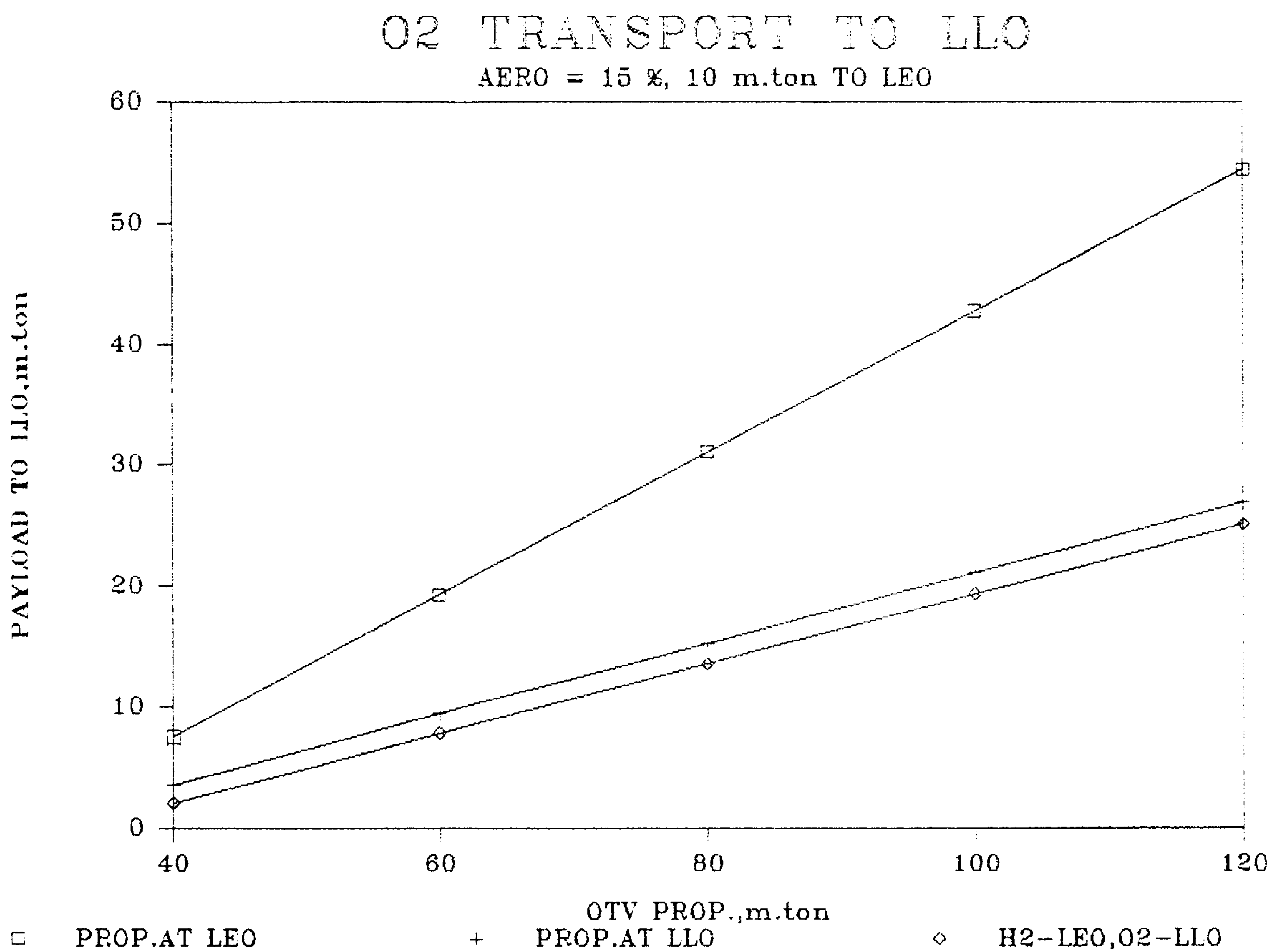
Trans-Lunar Injection (TLI)	=	3,155 m/sec + g loss
Midcourse Correction	=	60 m/sec
Lunar Orbit Insertion (LOI)	=	915 m/sec
Trans-Earth Injection (TEI)	=	915 m/sec
Midcourse Correction	=	60 m/sec
Circularization after Aerobrake	=	160 m/sec
Rendezvous	=	80 m/sec
Lunar Descent	=	2,165 m/sec
Lunar Ascent	=	1,920 m/sec

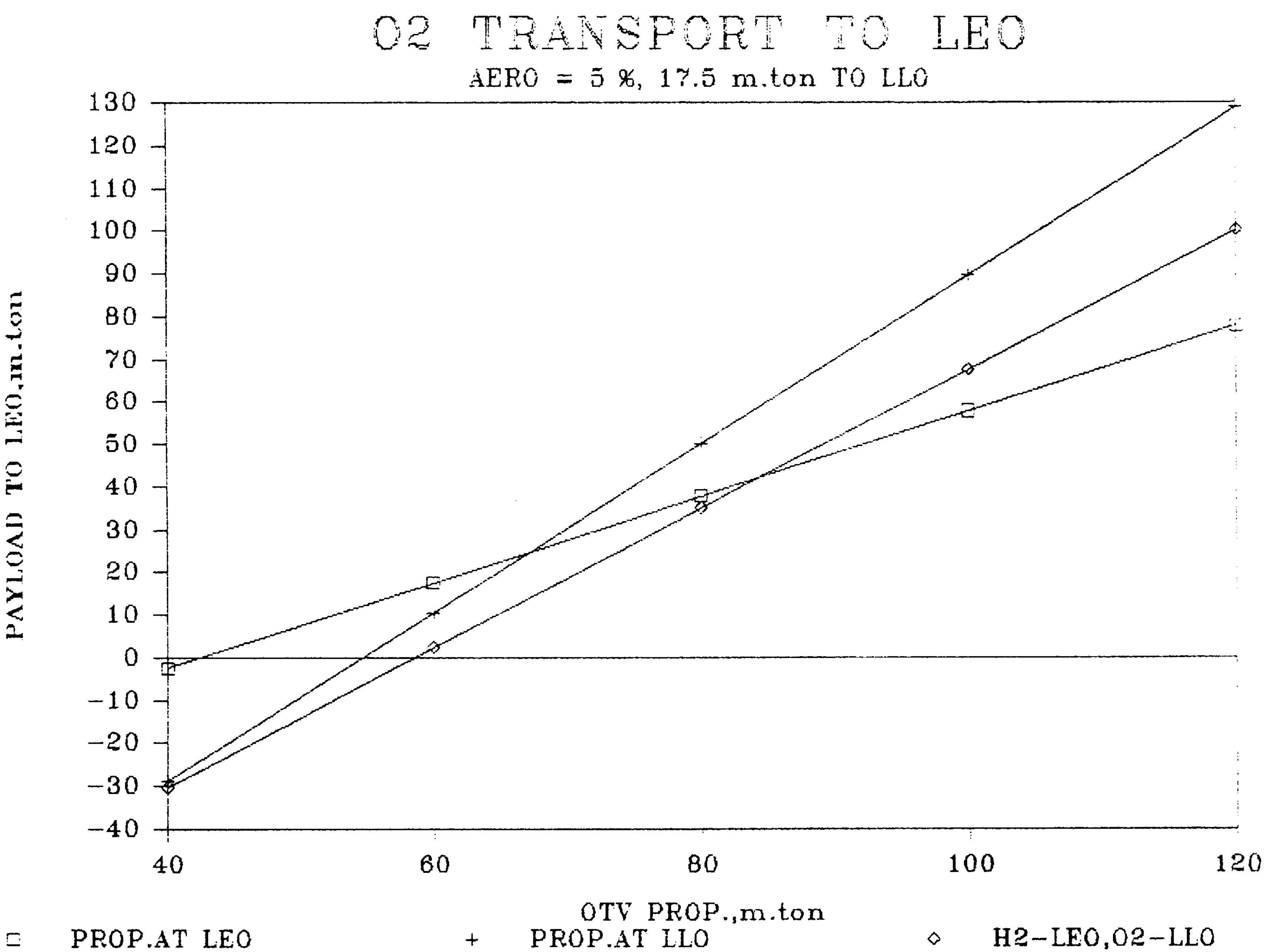

O2 TRANSPORT TO LEO
AERO = 5 %, ZERO TO LLO
PAYLOAD TO LEO,m.ton
220
210
200
190
180
170
160
150
140
130
120
110
100
90
80
70
60
50
40
30
20
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,02-LLO

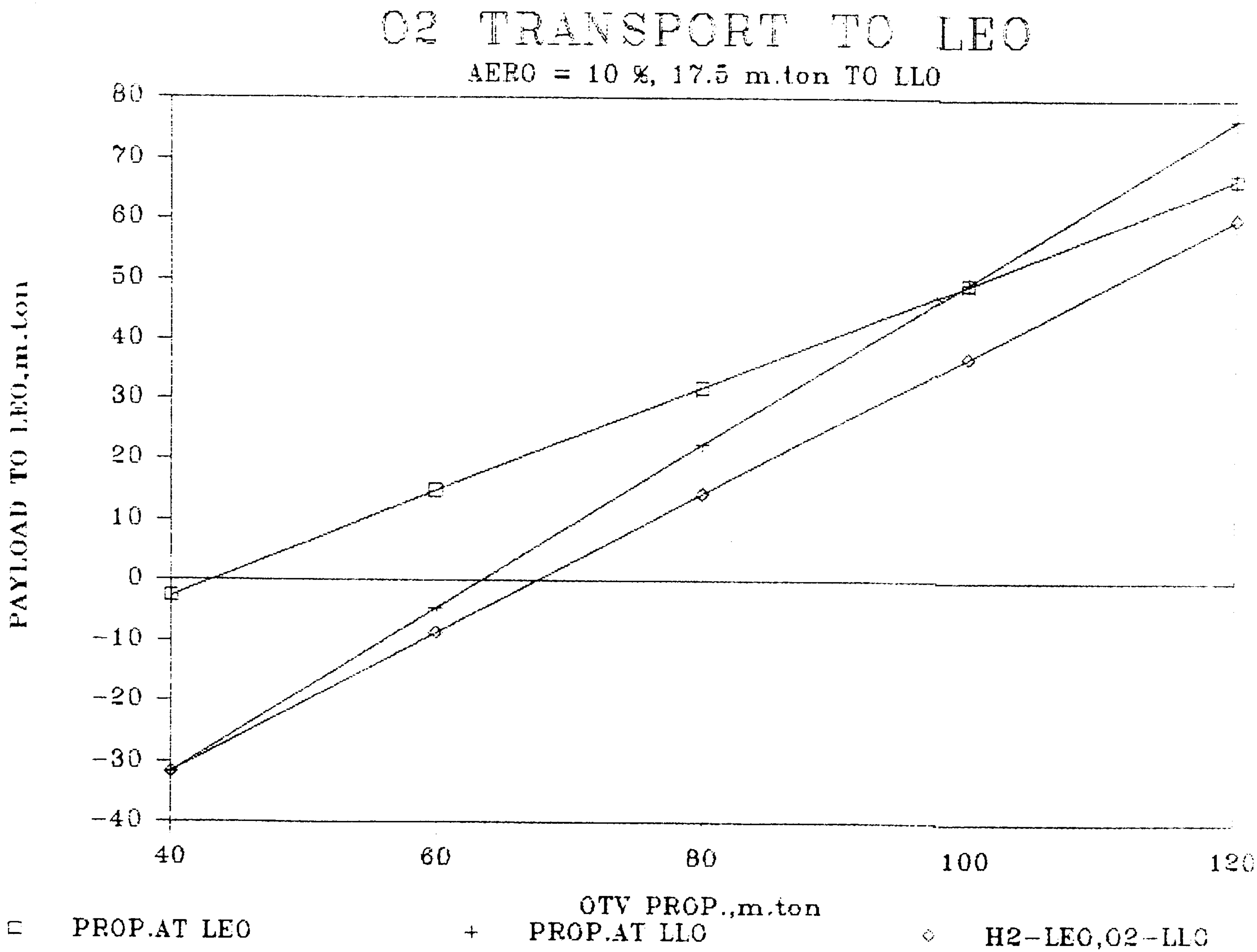

O2 TRANSPORT TO LEO
AERO = 10 %, ZERO TO LLO
PAYLOAD TO LEO,m.ton
150
140
130
120
110
100
90
80
70
60
50
40
30
20
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO

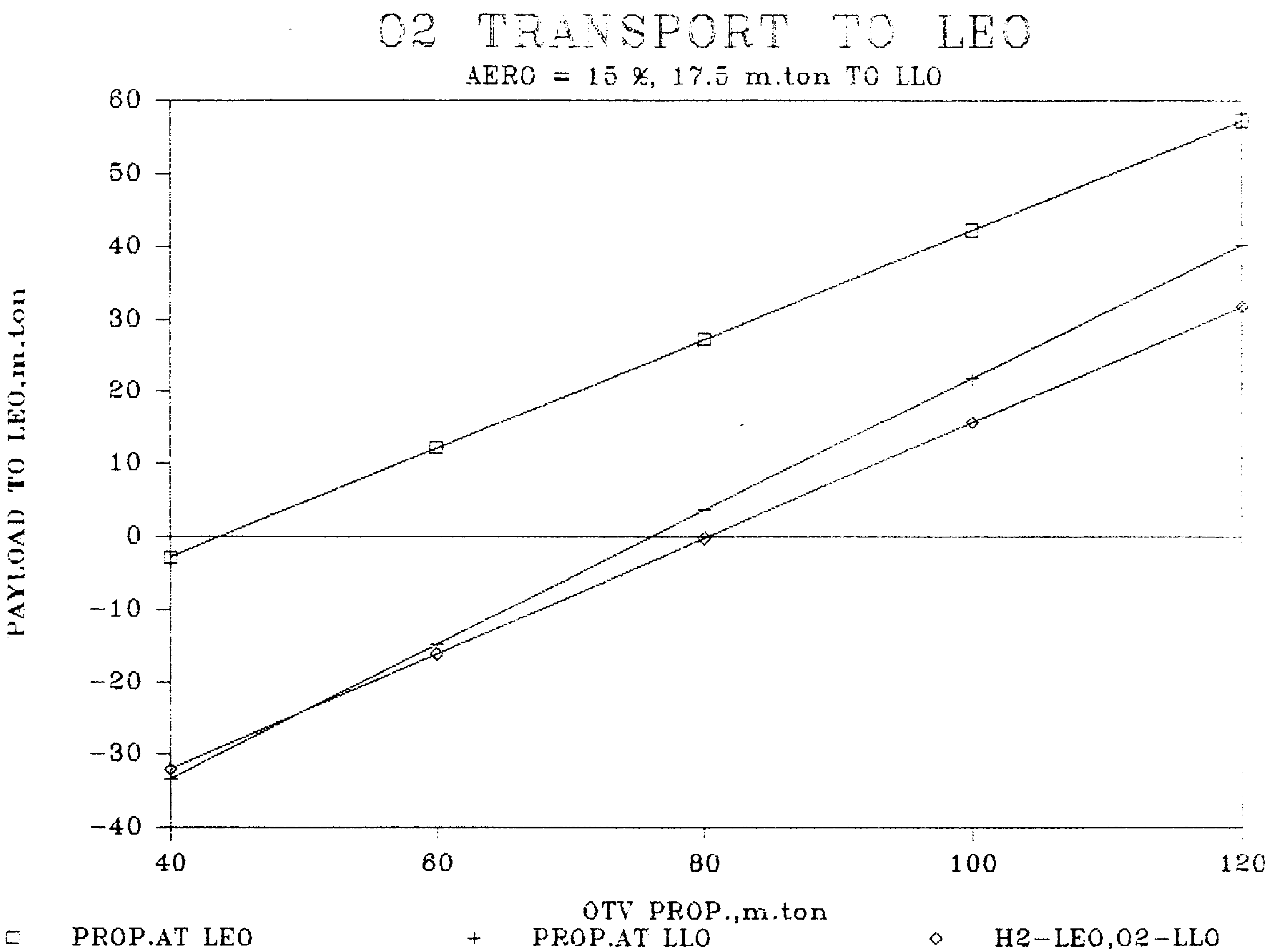

O2 TRANSPORT TO LEO
AERO = 15 %, ZERO TO LLO
PAYLOAD TO LEO,m.ton
100
90
80
70
60
50
40
30
20
10
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO


O2 TRANSPORT TO LLO
AERO = 10 %, 10 m.ton TO LEO
PAYLOAD TO LLO,m.ton
60
50
40
30
20
10
0
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO


O2 TRANSPORT TO LLO
AERO = 15 %, 10 m.ton TO LEO
PAYLOAD TO LLO,m.ton
0
10
20
30
40
50
60
40
60
80
100
120
OTV PROP.,m.ton
□ PROP.AT LEO
+ PROP.AT LLO
◇ H2-LEO,O2-LLO


O2 TRANSPORT TO LEO
AERO = 5 %, 17.5 m.ton TO LLO
PAYLOAD TO LEO,m.ton
130
120
110
100
90
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO


O2 TRANSPORT TO LEO
AERO = 10 %, 17.5 m.ton TO LLO
PAYLOAD TO LEO,m.ton
80
70
60
50
40
30
20
10
0
-10
-20
-30
-40
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO


O2 TRANSPORT TO LEO
AERO = 15 %, 17.5 m.ton TO LLO
PAYLOAD TO LEO,m.ton
60
50
40
30
20
10
0
-10
-20
-30
-40
40
60
80
100
120
OTV PROP.,m.ton
PROP.AT LEO
PROP.AT LLO
H2-LEO,O2-LLO